FR 838 1

R W B | RESEARCH

ELECTRONICS | PHYSICS

DEVELOPMENT OF NON-DESTRUCTIVE METHODS FOR DETERMINING RESIDUAL STRESS AND FATIGUE DAMAGE IN METALS

MONTHLY PROGRESS REPORT NO. 12
(ANNUAL REPORT)

PREPARED UNDER CONTRACT NO. NAS8-20208 BY

ROBERT W. BENSON AND ASSOCIATES, INC.

633 Thompson Lane

NASHVILLE, TENNESSEE 37204

ROBERT W. BENSON & ASSOCIATES, INC.
633 THOMPSON LANE • NASHVILLE, TENNESSEE 37204

DEVELOPMENT OF NON-DESTRUCTIVE METHODS FOR DETERMINING RESIDUAL STRESS AND FATIGUE DAMAGE IN METALS

MONTHLY PROGRESS REPORT NO. 12
(ANNUAL REPORT)

PREPARED UNDER CONTRACT NO. NAS8-20208 BY

ROBERT W. BENSON AND ASSOCIATES, INC.

633 Thompson Lane

NASHVILLE , TENNESSEE 37204

June 30, 1966

FOREWORD

This report was prepared by Robert W. Benson and Associates, Inc., Nashville, Tennessee, under NASA Contract No. NAS8-20208. The Contract was initiated by the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center. The work was administered under the direction of Mr. W. N. Clotfelter. This report includes work performed during the period 9 July 1965 through 8 July 1966.

The work was under the general direction of Dr. R. W. Benson. Mr. J. Ronald Chapman and Mr. Harold F. Huffman carried out most of the ultrasonic stress measurements. The electromagnetic measurements were under the supervision of Mr. Samuel H. Pearsall. Technical assistance was provided by Mr. J. L. Holladay, Mr. Richard T. Lee and Mr. Charles Phifer.

ABSTRACT

12227

The measurement of residual stress in structures is necessary to assure satisfactory performance from the material selected. Premature failure of a structure is often caused by the lack of knowledge of residual stresses since the design can only account for the superimposed loads due to external forces. The present program has been concerned with the development of nondestructive methods of stress analysis suitable for field application on actual metallic structures. Methods of providing a measurement due to uniaxial loads and due to bending momemts are described in this report. Experimental data is given showing the relationship between ultrasonic wave propagation and actual stresses. The techniques are demonstrated under laboratory conditions with practical stress distributions that can be encountered.

Additional effort was concerned with the detection of damage to metals by both fatigue and stress corrosion. The measurements included ultrasonic wave attenuation, electromagnetic resistivity and mechanical internal friction. All three methods show a capability of detecting the onset of failure by fatigue or stress corrosion but with the present techniques are insufficiently accurate to provide an inspection criteria. Refinements of the methods are possible and may lead to a successful method of measurement.

Author

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

I. INTRODUCTION

Inherent in a physical structure, there are stresses due to machining processes and due to the assembly of the parts within the structure. The result is an unknown state for the materials used which affects the performance of the structure. In order to design a particular structure for minimum weight it is necessary to know the exact effects of machining and fabricating processes which introduce stresses in a structure. Since the exact magnitude of the stress will change from structure to structure, it is necessary that the method of examination be nondestructive in nature so that a particular structure may be examined thoroughly. The present program was initiated to develop nondestructive methods for the measurement of stress distributions in practical structures. The methods to be developed should be capable of being applied in the field and should result in a quantitative determination of those stresses which may affect structural integrity.

In the past it was possible to construct models of particular structures using an optically transparent material which could be analyzed by photoelastic methods and would allow for the study and elimination of stress concentrations. These studies have been limited to those stresses which are due to assembly or due to external loading rather than stresses resulting from the processing of materials due to the necessity of substitution of an optically transparent material for actual metallic materials. These optical methods have been supplemented by more modern methods involving the use of various strain sensitive devices such as electrical strain gauges and brittle coatings which show changes in strain. In addition, procedures are available where a photoelastic material is bonded to a metallic structure and again the strain at a surface may be obtained. Unfortunately, all of these methods are limited to application after the basic machining processes have been completed. Furthermore, those methods of analysis which apply to metals are limited to measurement of strain rather than stress and therefore do not define the complete state of the material.

The ultrasonic method of stress analysis[1] has been based upon the photoelastic method and is similar in nature with the exception that transverse ultrasonic waves are substituted for polarized light waves. The ultrasonic method has the advantage that the waves propagate easily in metallic materials which are used for most structures. Furthermore, the ultrasonic method has the additional advantage that several forms of wave propagation are available which can allow for a more thorough analysis of complex geometrical structures. The frequency of the ultrasonic wave may be varied over wide ranges which allows for additional information over that which could be obtained by optical methods.

The exact state of a structure is determined not only by the actual stress distributions that exist but also is affected by the history of the forming processes which have been used. Materials may fail by such processes as fatigue when they have been subjected to repeated cycling at levels of stress below that which would cause failure upon application of an initial load. It has therefore been desirable to give attention to methods of measurement which might correlate with the state of the material for a specimen which has been subjected to repeated cycling

---

[1]"Ultrasonic Stress Analysis," Robert W. Benson, Ultrasonic News, Spring, 1962.

such as may occur during initial testing of a structure before actual use. Additional aspects which have been investigated are due to a combination of stress and the atmosphere to which the structure has been subjected. One of the most important types of failure is that of stress corrosion which is caused by corrosive atmospheres while the structure is under a state of stress. Since all of these factors affect the possible failure of a given structure it is desirable to be able to provide as complete a measure of the state of the structure as is possible. The current program has therefore emphasized not only stress analysis but measurements which may lead to a prediction of possible failure by either fatigue or stress corrosion.

II. SELECTION OF EXPERIMENTAL METHODS

A. Limitations in the Correlation of Destructive and Non-Destructive Stress Analysis Methods

A major objective of the program is to develop methods of measuring residual stress. Residual stress may be defined as those forces in a material which are due to the basic machining and fabricating processes rather than due to loads which are applied during use. It therefore may appear that major emphasis should be directed toward the study of materials which have been fabricated by many different processes in an attempt to determine those stresses which are due to each type of machining processes. Such an approach has the inherent limitation that it is necessary to correlate the method under study with some other method which is available that gives a more precise analysis. By this technique it would be possible to evaluate nondestructive methods under development against destructive methods which are not suitable for field application. There are a number of destructive methods available such as the application of strain measuring devices to a given part of a structure and the subsequent removal of portions of the material which provide stress relief. These methods have been used extensively but are subject to the limitation that most processes for providing stress relief also have the possibility of introducing additional stresses. An exception is the use of chemical etching which has an additional limitation of destroying most types of strain sensors.

Since the objective of this program was to develop stress measuring techniques rather than an evaluation of machining processes, it was felt that a more controlled set of conditions would be desirable. For this reason,most of the measurements have been made on structural members which have been subjected to external loading rather than those which may be due to machining processes. Any method that is capable of measuring residual stresses should also be capable of measuring those stresses due to external loading. It is possible to build loading frames which will subject a given structural member to complex forces producing a result similar to those which may be encountered when the stress is of a residual nature. With these loading frames it is possible to vary the magnitude of the stress and yet provide for direct measurements of the exact stress distributions. When a stress is successfully measured it is unimportant as to why the stress occured whether it be due to machining processes or external loading. In addition, an important kind of residual stress is due to the incorporation of a structural member within a complete structure and such stresses can easily be simulated within suitably designed loading frames.

B. Development of Ultrasonic Techniques to Measure Applied Stress

At the beginning of this program, several reports concerning ultrasonic stress analysis had already been issued. These reports were mainly concerned about the basic technique which shows a relationship between the change in velocity of propagation of ultrasonic waves and the state of stress in various metals. The initial experiments were similar in nature to photoelastic studies for which the state of polarization of an ultrasonic shear wave was measured as a function of stress. The measurements included a study of the effect of the ultrasonic frequency and demonstrated that the method provides a true measure of stress rather than strain. The initial measurements were limited to use under controlled laboratory conditions and were of little practical value for use under field conditions.

Since the basic method of ultrasonic stress analysis has been clearly demonstrated, the major effort was concerned with developing techniques which would allow for field applications. A number of approaches were explored during the initial period of the contract and those which appeared most promising were given more thorough development as the contract progressed.

The most simple stress that can be encountered is that due to uniform uniaxial loading of a member. The method of analysis is simple in principle and is only complicated by factors concerning field use. The ultrasonic waves which are generated are derived from quartz crystals vibrating in shear which must be coupled to the surface of a sample under study. For laboratory measurements, the crystals may be waxed on to the surface in a manner which assures good signal levels and consistent results. For this reason the basic methods were first selected to be studied under ideal repeatable laboratory conditions. All possible methods were studied because of possible merits of one particular method over others when the problem of field coupling of crystals is introduced. Variations of two basic methods have been studied extensively; a determination of the angle of polarization of an ultrasonic shear wave and the relative velocities of two shear waves propagating along the major axes of stress. The first of these methods is dependent upon the measurement of the relative amplitude which is subject to considerable variation with the bonding of crystals to the sample. The second method measures the relative time to traverse a sample and is independent of amplitude thus making it more suitable for possible field applications. These particular measurements are described in detail in the next section of this report.

The next most complex stress that is encountered is that due to bending moments such as are introduced in the formation of cylindrical surfaces. If the above techniques are used it is found that the average stress encountered in traversing the thickness of a specimen is near zero since there is ordinarily a maximum tensile stress near one surface and a maximum compressive stress near the other surface. Since the ultrasonic wave propagates through both tension and compression the effects nullify each other indicating an average stress near zero. It is therefore necessary to select methods of study which involve a portion of the material under constant stress. The ultrasonic surface wave is ideal from this view point since it also is a transverse wave and may be caused to propagate near the surface to a depth of penetration dependent upon wave length. Another form of inspection that is possible is that due to the refraction of waves as they propagate through a medium where the velocity is a function of the thickness.

C. Evaluation of Various Ultrasonic Techniques

Ultrasonic waves may be caused to enter a metallic specimen at any angle that is desired. A second material may be chosen whose velocity is slower than that of the metal under observation so that a bending of the wave occurs at the interface. The actual path of the wave is determined by the relative velocities and the angle of incidence at the interface between the two materials. Although lucite is used commonly as the slower velocity material, studies have also been made using water and mercury. As the angle of incidence of the sound wave is varied it is also possible to create a mode conversion at the boundary so that the form of wave may change from a longitudinal wave to either a shear wave or a surface wave. Since it has already been established that the velocity for shear waves is a function of stress the shear wave mode conversion was selected for study. In samples subjected to bending moments it would be indicated that there is a continual change in velocity for a shear wave as it traverses through the thickness of the sample. A wave that traverses the sample will be subject to a bending which is due to the change in velocity (velocity gradient) and thus should be related to the stress gradient in the sample. Studies were made using shear waves which were propagated in the sample at angles between 50° and 80° from the normal where the objective was to determine any bending of the wave front due to stress gradient. Although it was possible to find a measurable effect due to the presence of the stress gradient there are complications which severely limit this method as being satisfactory for stress analysis. Theoretically, the entire wave front propagates at a single angle of incidence and follows a narrowly confined path. In practice the beam spreads considerably, especially for angles of the order of 70° to 80° from the normal which would result in a maximum sensitivity to the stress gradient. Sufficient measurements were made to determine that the desired phenomenon exists but cannot be measured with sufficient accuracy to be a useful technique.

As a result of these studies it was found that a single transducer using a lucite wedge of approximately 60° angle of incidence was capable of generating a good shear component and, in addition, a good surface wave. This led to additional studies where the velocity of a surface wave was compared to the velocity of a shear wave propagating in the same sample. Measurements were made on both the shear wave component and surface wave component independently and it was found that the shear wave component had an average velocity which is essentially constant with varying stress. The surface wave velocity is proportional to stress. It was hypothesized that a reference to the shear wave would be ideal since changes in the composition of the material might similarly affect the basic velocity of both waves under conditions of no stress and that an absolute velocity measurement could be avoided.

Under laboratory conditions the sending and receiving transducers are fixed in position and the stress is varied which results in a relationship between stress and the observed change in velocity. In order to make a field measurement the stress is constant due to either the formation processes or external forces and the measurement must be accomplished upon application of the transducers. It is therefore obvious that certain factors must be closely controlled if a successful measurement is to be made under field conditions.

The velocity of the surface wave can be determined if the distance through which it propagates and the frequency which is used are accurately controlled. The lucite wedge type of transducer contacts a considerable area of the sample and must be coupled to the sample by some type of oil film. The exact path length under these conditions is difficult to define and impossible to repeat. For this reason emphasis was shifted to possible transducer designs which would allow for a fixed path length which could be accurately controlled. If the frequency of measurement is known and the path length is fixed it is possible to measure the surface wave velocity in different directions and determine the magnitude of the stress. The initial design of such transducers and the results obtained therefrom are described in detail in the next section of this report.

The program has thus far demonstrated a number of different techniques which may be used under laboratory conditions to measure stress. Several of these methods have considerable merit for field applications and are under current evaluation. The choice of several forms of wave propagation which show a dependence on stress should result in a sufficient number of methods of examining a structure so that practical stress analysis under field conditions will be possible.

III. ULTRASONIC VELOCITY-STRESS MEASUREMENT PROCEDURE AND RESULTS

A. Ultrasonic Measuring System and Technique

It has been found that both ultrasonic shear and surface waves have a stress-velocity dependence. With these two types of ultrasonic waves it has been shown that stresses in the bulk of a material as well as surface stresses can be measured accurately on a relative basis. There have been several methods considered by which the velocity change could be measured, and it was found that the most accurate method was a modified "time of flight" procedure. A block diagram of the system is shown in Figure 1.

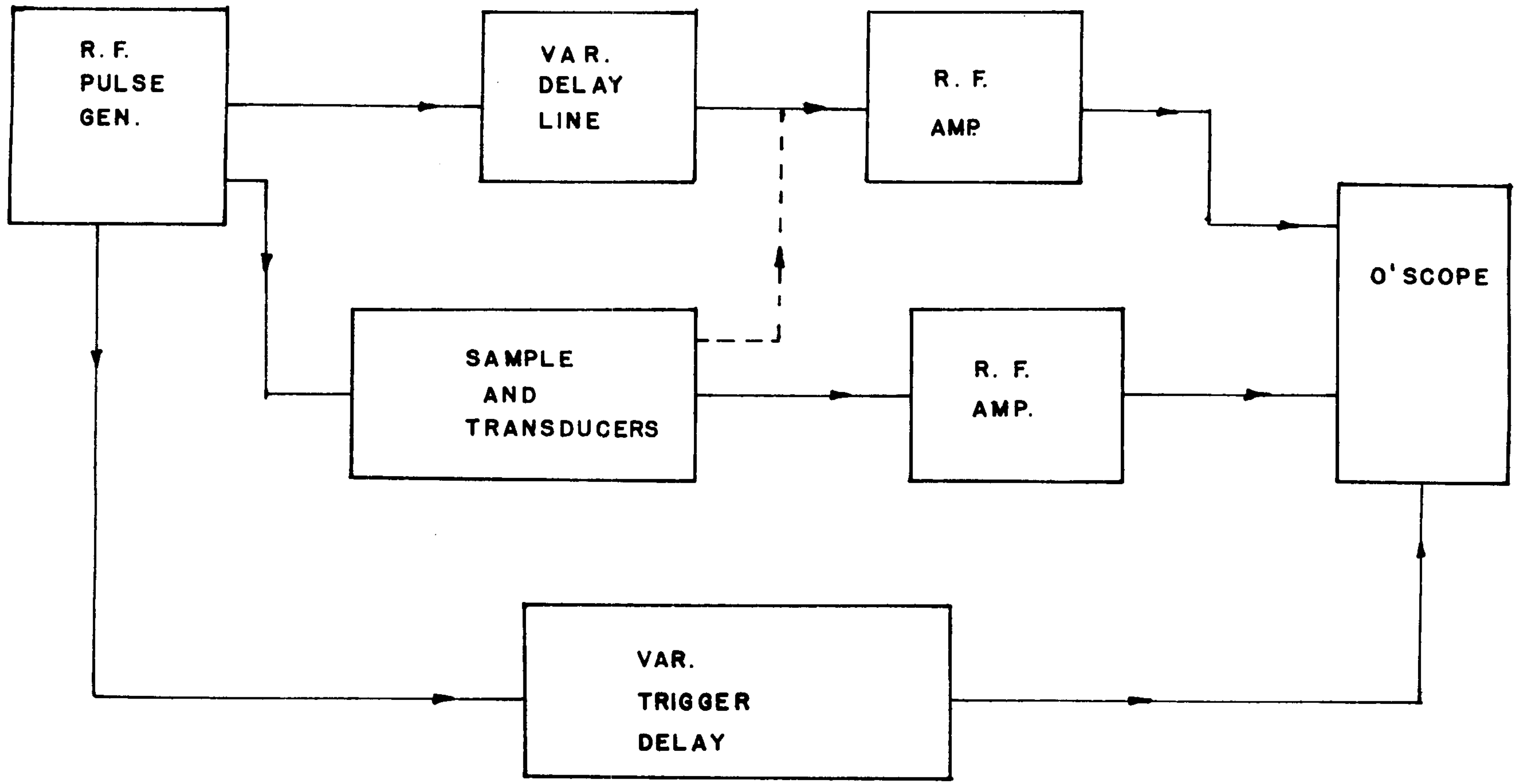


Figure 1. Block Diagram Showing the Basic System Used in Measuring the Change in Velocity of Ultrasonic Shear and Surface Waves.

The RF pulse generator used in the basic system shown above has an output voltage of 400 volts peak to peak fed from a link couple. With appropriate plug in coils the output frequency covers a range from 1 to 50 MHz. The duration of the RF pulse is variable from 1 to 10 microseconds at a repetition rate of 1 KHz. Generally speaking, the pulse width used in most of the modified "time of flight" experiments is 4 microseconds which gives sufficient time for the vibrational build-up of the crystal transducer to occur. Although the particular RF pulse generator was constructed in the laboratory, similar equipment can be obtained commercially.

The RF amplification of the received signals is achieved by commercially produced RF amplifiers especially designed for pulsed systems. In some cases, specifically with shear crystals bonded with wax, no amplification is needed since the voltage generated at the receiving crystal is of the order of tenths of a volt. However, amplification is necessary for measurements conducted on surface waves generated by lucite wedges at frequencies above 5 MHz where the received signal at the crystal is only at the millivolt level. Lower frequency surface wave signals are strong enough so that no amplification other than the oscilloscope is needed. The RF amplification system when used consists of a tunable preamplifier designed to operate from 5 to 60 MHz with a typical gain of 20 to 40 db over the above frequency range. The preamplifier is followed by a wideband amplifier with an adjustable gain of 0 to 65 db from 5 to 60 MHz.

The variable trigger delay is basically a single shot multivator triggered at the initiation of a pulse by the RF pulse generator. Triggering of the oscilloscope occurs when the single shot returns to its normal state. The delay time of the trigger is continuously variable from 1 to 100 microseconds with a positive output voltage spike of 3 volts.

The output of the RF pulse generator is applied to the sending transducer attached to the sample as well as the transducer on a variable delay line. The delay line used employs a pair of surface wave transducers whose path length can be changed with a traversing mechanism. By changing path length the time necessary for the surface wave pulse to reach the receiver can be changed. Therefore, the received pulse from the delay line can be adjusted to occur at any reasonable time after the RF pulse is applied to the sender. In some cases the measurements taken with the shear waves did not utilize the delay line as will be explained later. In any case, the delay line or reference signal provides an RF pulse that can be placed in time so that it coincides with the received pulse from the sample. The delayed trigger, shown in the diagram, is then used to start the oscilloscope trace at the time of arrival of the first received pulse.

The particular oscilloscope shown in Figure 1 had a dual channel plug-in amplifier with a bandwidth from 0 to 25 MHz and a sensitivity of 0.005 volts per centimeter. It is possible to display each of the inputs of the oscilloscope amplifier alternately so that signals from the delay line and sample could be viewed simultaneously on two traces. Furthermore, the oscilloscope is equipped with an internal delay trigger. By this means it is possible to delay the time of initiation of one of the traces.

The actual procedure involved in making the modified time of flight measurement is not very complicated. For example, suppose a sample is to be investigated and it takes 20 microseconds for the signal to transverse the specimen. The variable delay trigger is turned to its minimum delay time of 1 microsecond. With the time base of the oscilloscope set at 5 microseconds per centimeter, the trace displaying the received signal from the sample would show the received RF pulse at approximately the middle of the oscilloscope screen. The received delay line signal, which is viewed on the other oscilloscope trace, is made to coincide in time with the signal wave transducers of the delay line. Once the delay line has been adjusted properly, the variable delay trigger is then adjusted so that the oscilloscope traces are initiated at approximately 20 microseconds after the RF voltage was initially applied to each of the senders. After this adjustment the received signals appear at the beginning of the oscilloscope trace.

The time base is then changed to 0.1 microsecond per centimeter. With this setting and the RF frequency of the pulses is in the region of 3 to 10 MHz, the pulses on each trace appear as if they were continuous sine waves. Also it is important to point out that it is possible to visually observe a phase shift between the two signals. Before any stress is applied to the sample the two signals are brought in phase with each other by adjusting a calibrated 10-turn potentiometer which controls the internal delay trigger of the oscilloscope. The amount of delay time necessary to visually bring the signals in phase can then be read directly from this calibrated potentiometer. It is possible to read delay times of 10^{-9} seconds.

As stress is applied to the sample the velocity of the ultrasonic wave changes. This means that the time it takes the wave to transverse the sample is changed. When this change occurs a phase shift between the sample signal and the delay line signal is visually noted on the oscilloscope. The internal trigger can then be adjusted to bring the signals in phase. The change in time of travel through the sample then corresponds directly to the time necessary to change the internal trigger for phase alignment. In other words, if the delayed trigger shows a delay of 150×10^{-9} seconds and the two signals are in phase, application of stress makes the signals slip in phase. To bring the signals in phase again requires, for example, the internal trigger to be further delayed by 20×10^{-9} seconds. Therefore, the applied stress produced a 20×10^{-9} second change in the travel time of the ultrasonic wave.

Normally, the oscilloscope connections are made so that the trace displaying the delay line signal is the one affected by the internal trigger. As a result, if the signal from the sample is delayed, i.e., the velocity decreases, the internal delay trigger is adjusted so that the initiation of the trace showing the delay line pulse occurs earlier.

B. Shear Wave Experiments

The property of a material that makes it suitable for measuring stress is that it exhibits the phenomenon of birefringence. In other words, the polarization of the particle motion, which is perpendicular to the direction of propagation, changes from linearly polarized to elliptical, to circular, etc., and then back to a linearly polarized wave, as it travels through a stressed sample. Experiments were performed in order to find the best way that the birefringence could be measured. One of the simplest methods is shown in Figure 2 where two Y-cut crystals, a sender and a receiver, are placed on the sample at 45° with respect to the direction of a uniaxially applied load. As the load is applied, the received signal will go through maximums and minimums as a result of the change in polarization. Typical data for this method of measurement is reproduced in Figure 3. It should be noted that these measurements are dependent on amplitude and are therefore subject to the inaccuracies of measuring amplitudes.

A different method using the basic scheme shown in Figure 4 proved to be the most accurate in obtaining a velocity stress dependence characteristic of the shear wave. A Y-cut sending crystal was bonded with wax at 45° with respect to the uniaxially applied load. The particle motion of the generated shear wave being transverse to the direction of propagation can be broken down into two equal components. One of the components is parallel to the axis of the load while the other one is perpendicular to it. As mentioned earlier, the wave undergoes a change in polarization if the medium is subjected to stress. In other words, this means that one or both components of the wave travels at a slightly different velocity depending upon stress in order to give the necessary time phase change for polarization to occur. Therefore, if two Y-cut crystal receivers are oriented so that they independently receive the two components, the velocity change with stress can be observed.

The basic measuring system shown in Figure 1 was used in making the velocity-stress measurements of the shear wave.

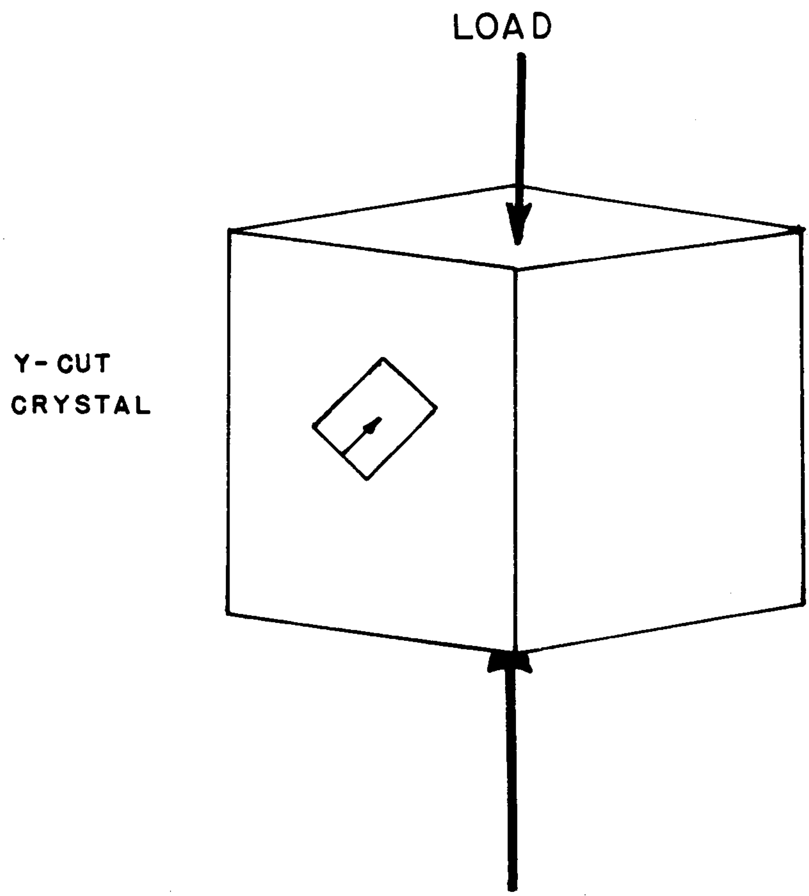


Figure 2. Crystal Orientation for Showing the Change in the State of Polarization of an Ultrasonic Shear Wave Versus Stress.

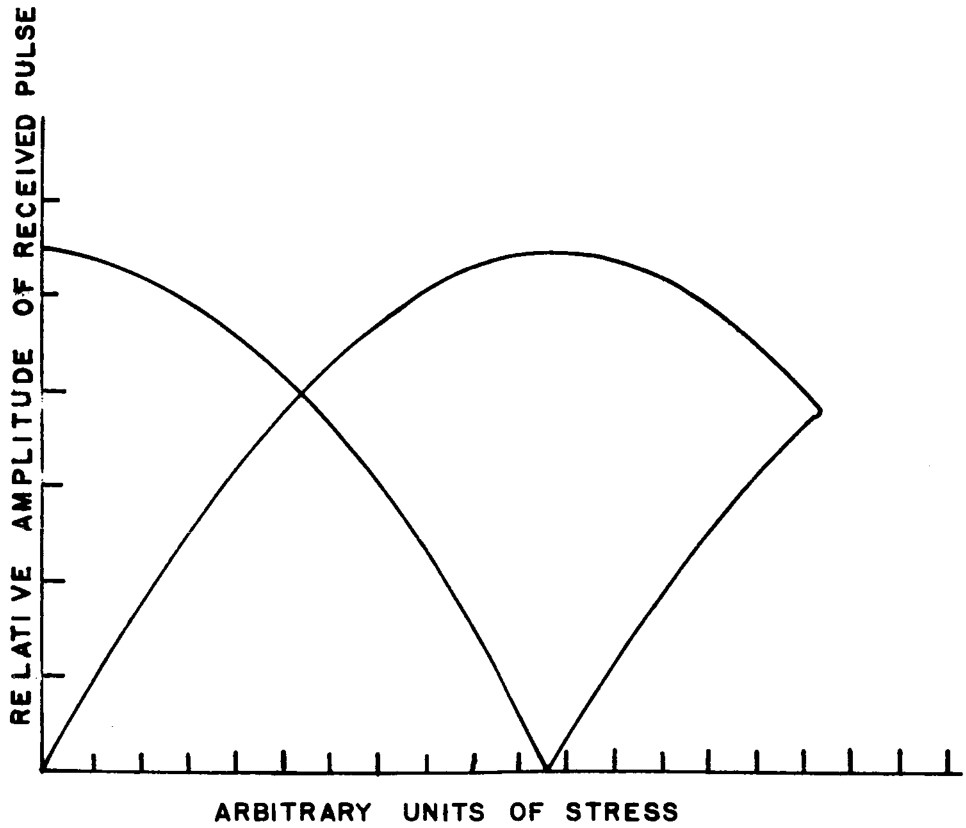


Figure 3. Amplitude of Received Shear Wave Versus Stress Indicating the Change of Polarization of the Ultrasonic Wave.

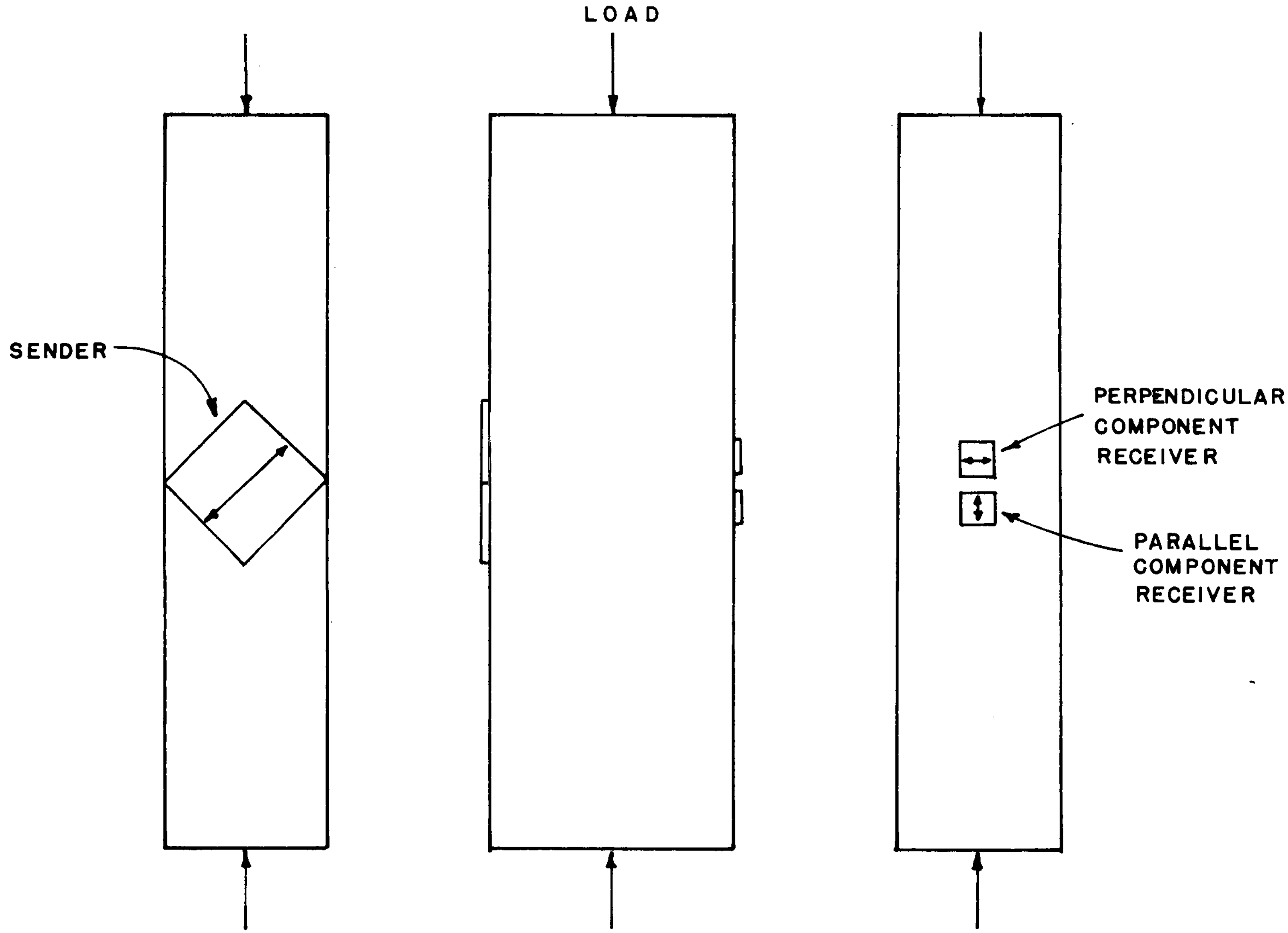


Figure 4. Crystal Mounting Used to Detect Various Components of a Shear Wave.

As the sample was compressively stressed, each component of the received wave was phase compared to the delay line in the fashion described earlier. The sample was stressed in successive increments up to a stress 24 x 10^3 psi. The graph of Figure 5 shows the change in time of flight of the shear wave versus stress. It is noted that the parallel component of the shear wave increases in velocity linearly with compressive stress while the perpendicular component decreases in velocity linearly with stress. Another measurement was made which eliminated the need for the delay line. In this case, the parallel and perpendicular components were phase compared with each other. This is a differential type of measurement where factors such as path length changes due to strain and changes in density throughout the sample do not affect the measurement since both signals travel essentially the same path length. Verification that the differential type of measurement is valid can be seen by graphically subtracting the curve representing the perpendicular component from the curve of the parallel component.

The particular set of curves in the graph of Figure 5 was taken for the aluminum alloy 7075. Similar data was also taken for 6061 and 2024 aluminum alloys. Table I gives important data for alloys tested. The samples used to obtain the data were 1" x $1\frac{1}{2}$" x $4\frac{1}{2}$" inches long, loaded uniaxially along the long dimension. Seven MHz transducers were placed on the 1" sides giving a path length of $1\frac{1}{2}$" for the ultrasonic shear wave. The sides on which the transducers were attached were initially polished with carborundum paper containing #500 grit.

Further work is now being conducted concerning the application of shear waves to field use in measuring stress. A transducer has been constructed which can be used from one side of a specimen. Figure 6 shows a sketch of the transducer. Two Y-cut crystals are mounted with their axes of vibration at right angles. These crystals are used to generate and receive signals and a phase comparison is then made to determine the change in velocity. The amount of phase shift between the two signals is then proportional to the average stress difference between the two directions of vibrations as reported above. Of course, the laboratory

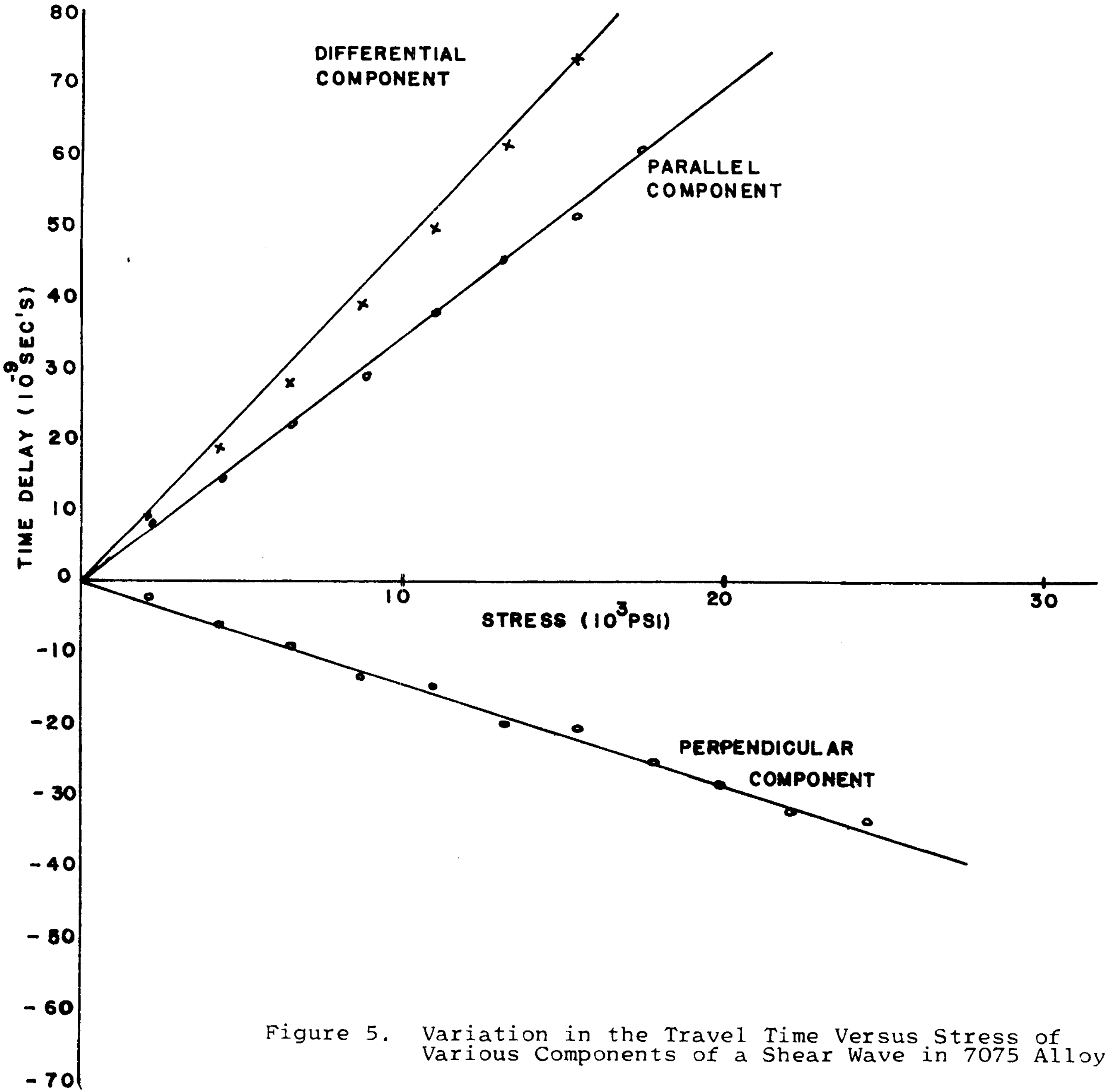


Figure 5. Variation in the Travel Time Versus Stress of Various Components of a Shear Wave in 7075 Alloy.

TABLE I

Acoustical Velocity Data*

Characteristic	Alloy 2024	6061	7075	
Temper	T351	T651-T6	T651	
Modulus lb/in^2	$10.6x10^6$	10^7	$10.4x10^6$	
Yield lb/in^2	$47x10^3$	$40x10^3$	$73x10^3$	
Delay Time for 1" Path Length at 10^3 psi, Strain Corrected	1.93nsec. 1.04	3.32nsec.- .556	3.61nsec. .239	(Shear Wave) (Surface Wave)
Delay Time at Yield for 1" Path length (nanoseconds)	90.8 48.8	133 22.2	263 17.5	(Shear Wave) (Surface Wave)
Absolute Velocity Shear Wave - Meters/Sec.	3300	3045	3480	
Absolute Velocity Surface Wave Meters/Second	3030	2905	3030	

*Measurements were made at 7 megacycles per second with the exception of Surface Wave Data for 7075 which were made at 5 megacycles.

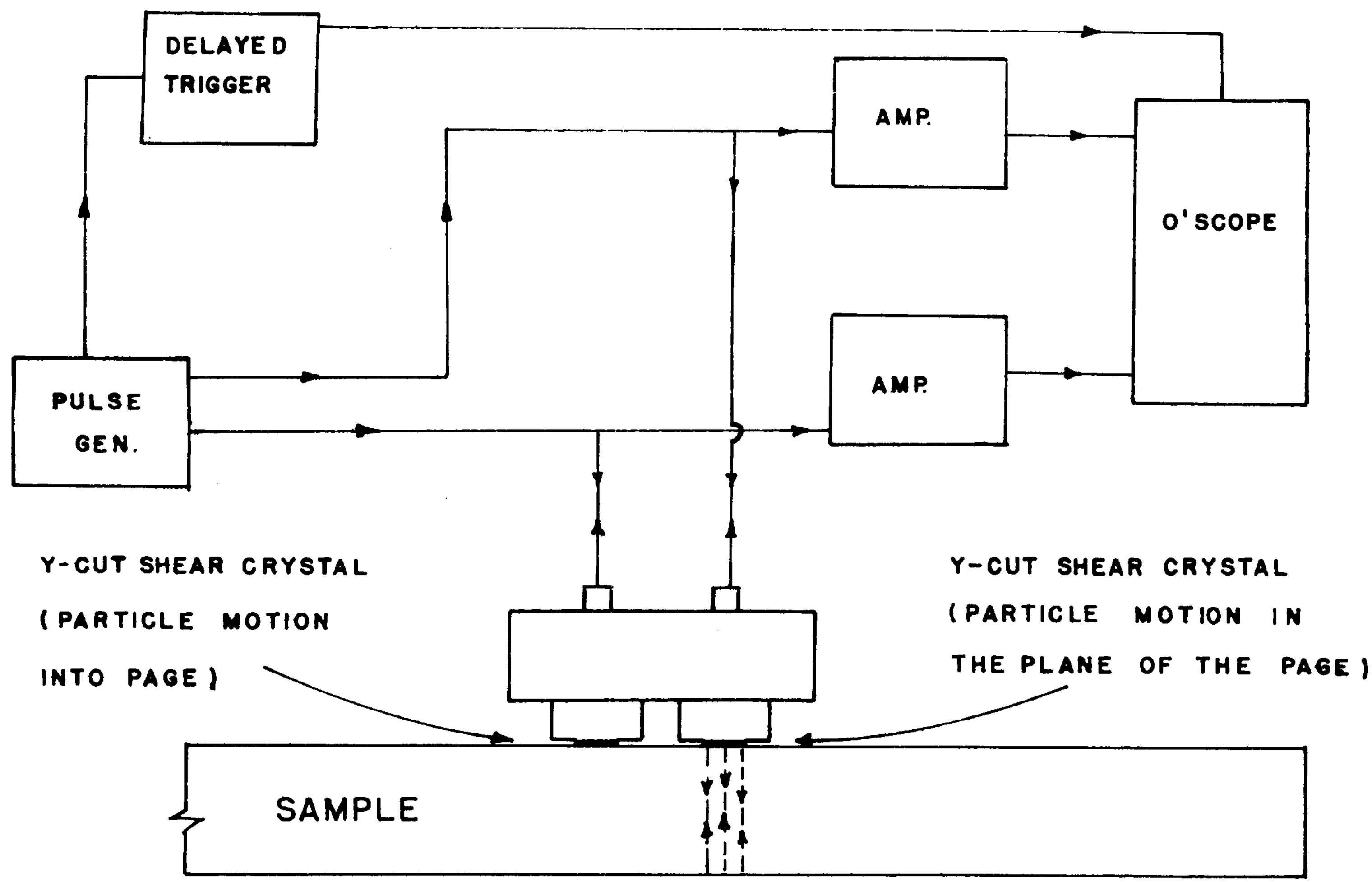


Figure 6. Shear Wave Transducer and Associated Equipment for Measuring Stress from One Side of the Sample.

experiments with shear waves performed to date have dealt mainly with uniaxial loads. However, the single side type of transducer enables not only the principle direction of stress to be found but also its magnitude. For example, if the direction of stress is a sample is in the direction of its particle vibration of one of the crystals, the maximum differential change occurs. Orienting the transducers by 45° should then show no change since both components of the shear wave see the same amount of stress. Incidentally, this is a means by which calibration of a zero relative stress can be made.

There are, however, certain problems involving errors in measurements due to couplants with any type of ultrasonic transducer that is basically a portable device. Shear waves are especially difficult to couple into a sample, but development work is now being conducted in order to evaluate couplants suitable for field use.

C. Surface Wave Studies

Not only do shear waves show a velocity-stress dependence but so do surface waves. This type of ultrasonic wave is extremely useful in studying surface phenomena such as surface stress, surface conditions, such as oxide coatings, and stress gradients. All of the mentioned phenomena can be studied with the basic measuring system shown in Figure 1. The velocity-stress dependence of the surface wave was measured for the same alloys used in making the shear wave measurements, i.e., 2024, 6061 and 7075. The surface wave was compared against the delay line of Figure 7, as the samples were stressed uniaxially and the obtained data can be found in Table I. (See Page 19.)

The same samples described earlier in the studies of shear waves were used to obtain the surface wave data. The wedge transducers were placed at 1, $1\frac{1}{2}$ and 2 inches apart on the 1 inch side of the sample as shown in the Figure. For each of these spacings data was taken over the same stress range.

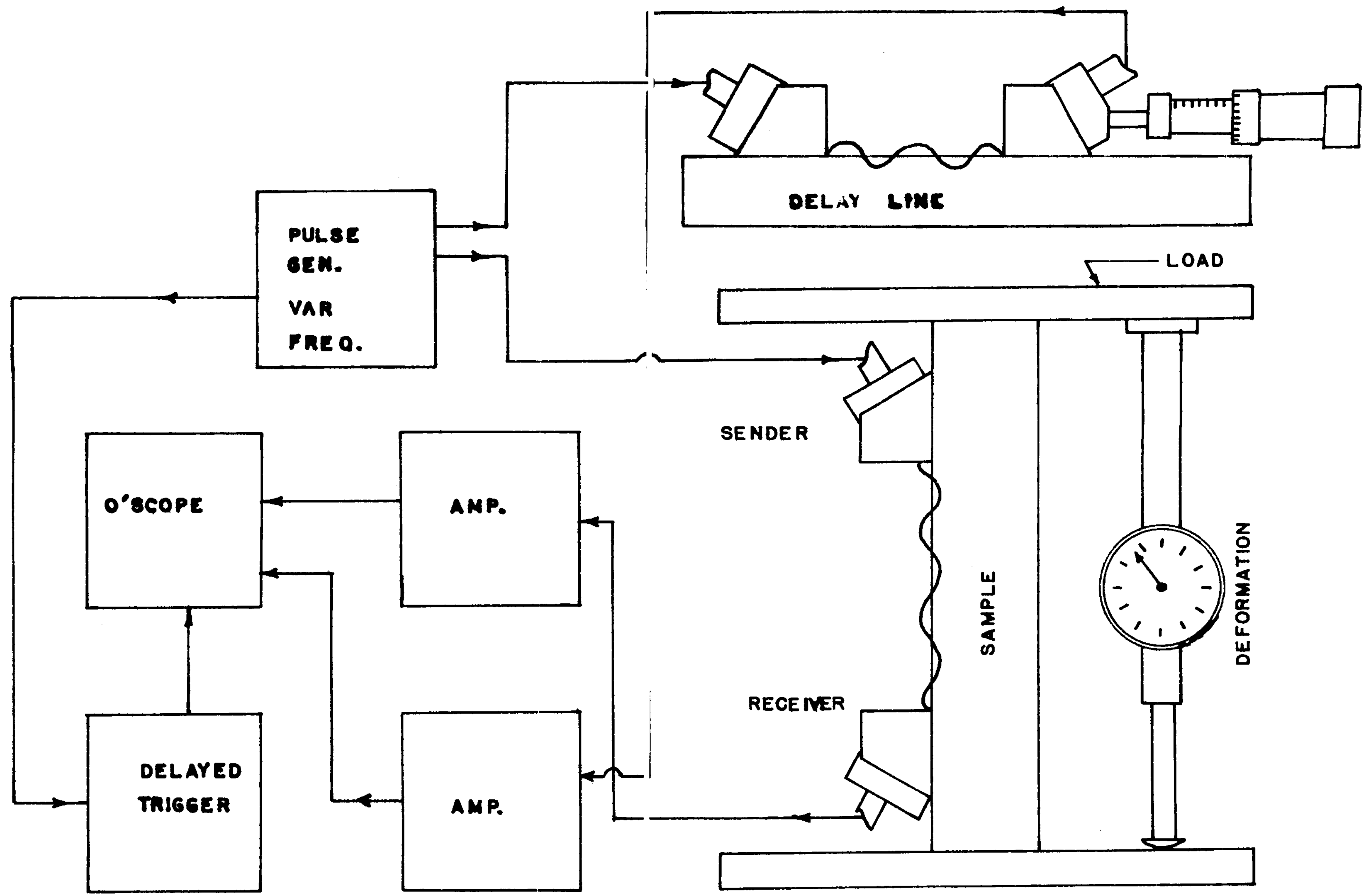


Figure 7 Surface Wave Velocity Measurement Configuration Illustrating the Use of the Delay Line.

It should be pointed out that the measurements concerning surface waves are affected by strain. Generally speaking, one half of the change in the time of travel of the wave on a stressed sample is due to stress, the remainder being a result of path length change due to strain. This fact should not complicate field measurements since it can easily be corrected by calibration.

Data was also obtained concerning the velocity change of the surface wave with stress using the loading apparatus shown in Figure 8. This loading frame applies a bending moment to the sample so that its top fiber can be subjected to either tension or compression by simply interchanging the supports. Between the two inner supports there exists a constant bending moment causing the stress along the surface of the sample in the region to be constant. The value of the stress is calculated by knowing the deflection of the sample. The surface wave data obtained is illustrated graphically in Figure 9. Note that the linear relationship between velocity change and stress holds in tension as well as compression. The solid line without data points shows the actual velocity change when the obtained data is corrected for strain.

The sample size used in the loading frame was 1" x $1\frac{1}{2}$" x 48" long. The 1" side was polished with #500 grit paper. The pictures of Figure 10 shows the loading frame and the placement of the sample.

Another advantage that the surface wave possesses is that its depth of penetration can be controlled simply by changing frequency. The penetration depth of a surface wave is approximately one wavelength. For example, with a surface wave velocity of 3 x 10^3 m/sec the depth of penetration is 0.3 cm at 1 MHz, or .03 cm at 10 MHz. Stresses that are present near the surface of a material and vary with depth can then be measured by varying frequency.

D. Stress Gradient Studies

A stress gradient was produced in the laboratory by subjecting a sample to a constant bending moment by the loading apparatus shown in Figure 8. With this type of loading,

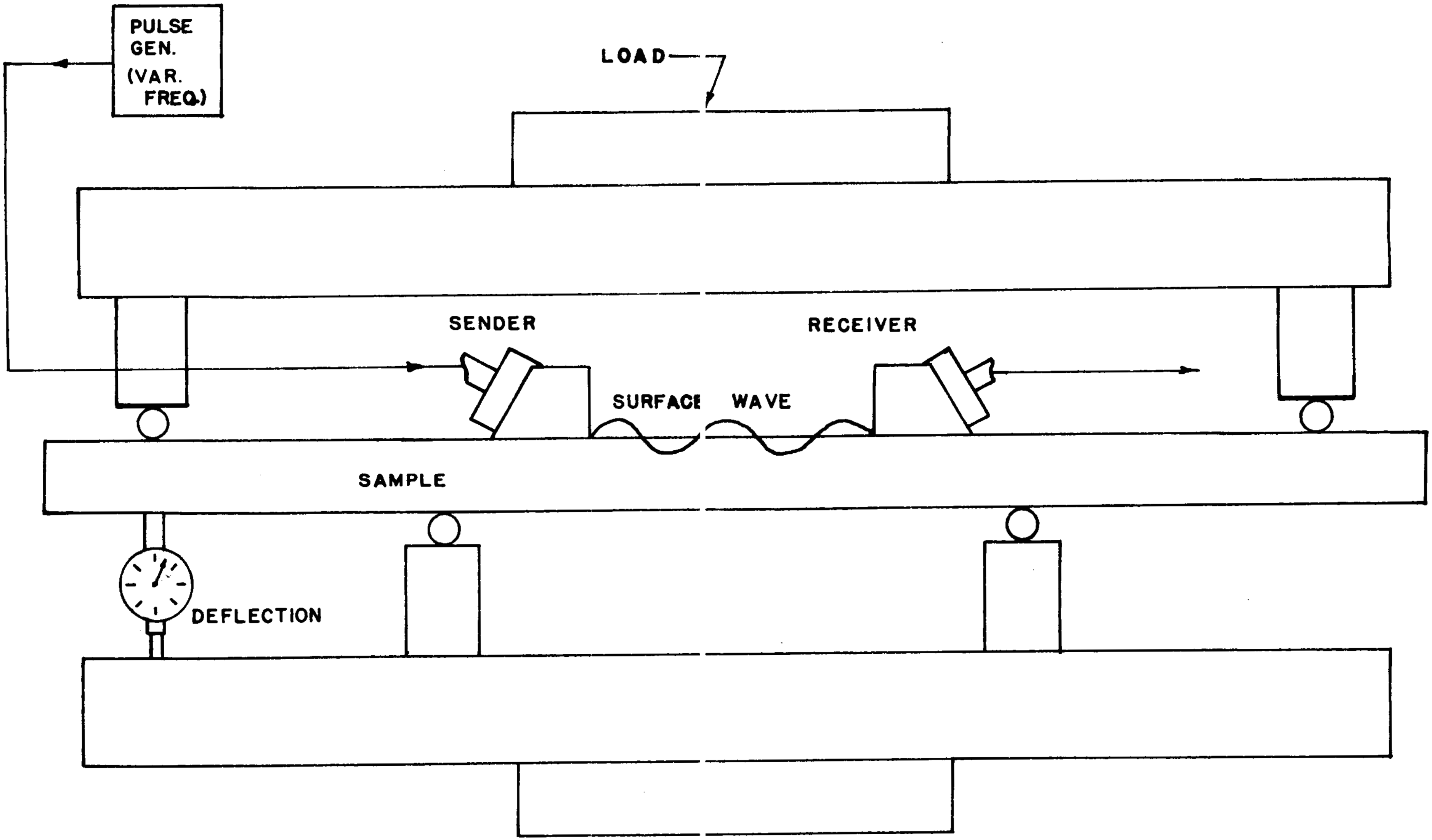


Figure 8. Loading Frame Used for Producing a Bending Moment in a Sample.

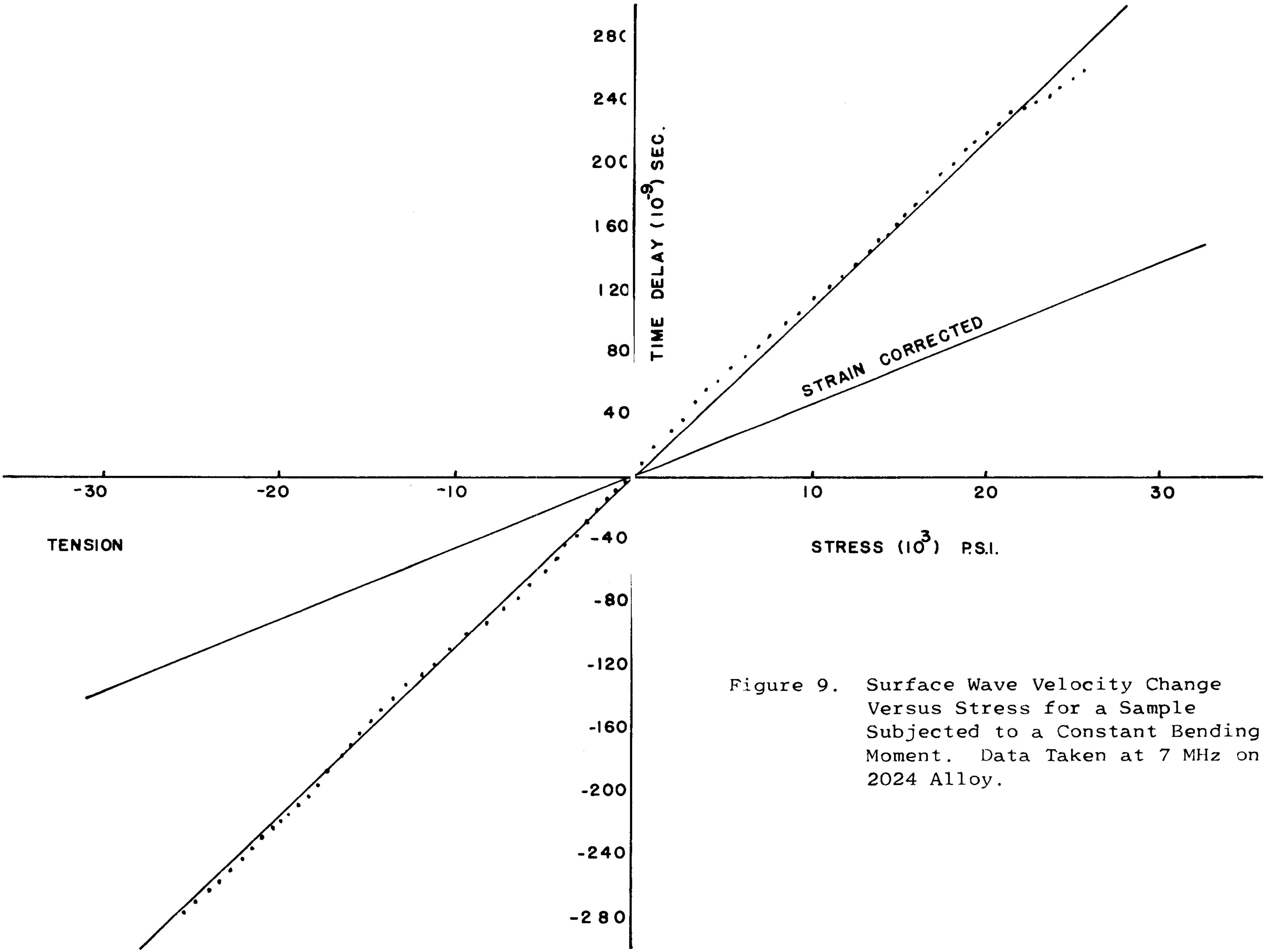
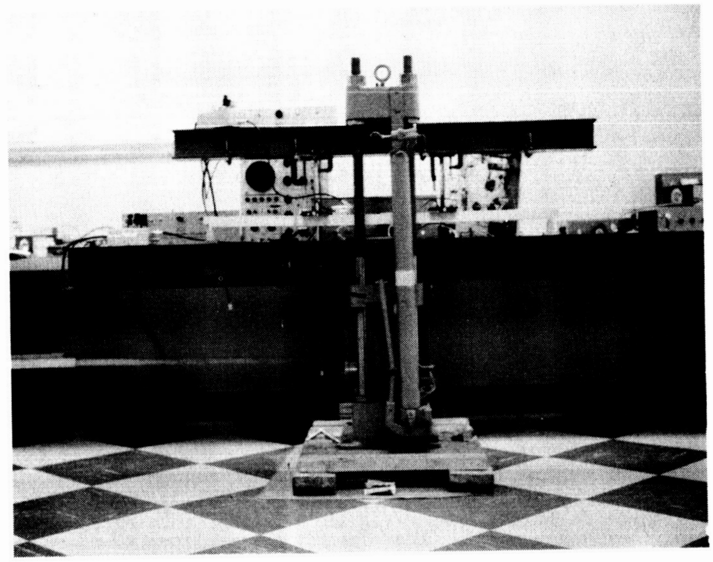


Figure 9. Surface Wave Velocity Change Versus Stress for a Sample Subjected to a Constant Bending Moment. Data Taken at 7 MHz on 2024 Alloy.



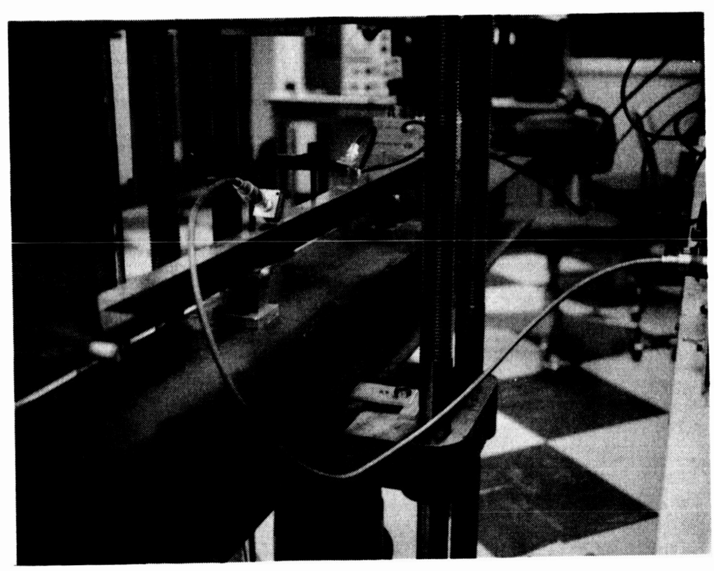


Figure 10. Illustrating the Loading Frame for Producing a Bending Moment.

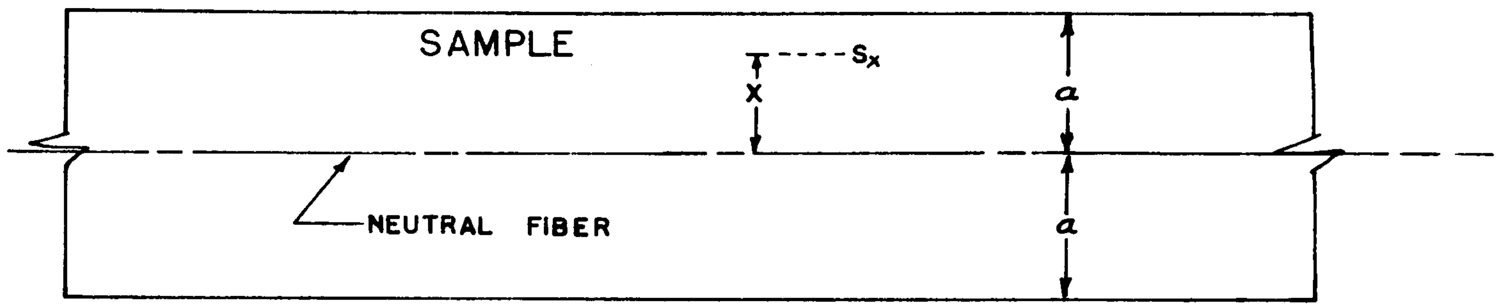
the stress in the sample varies linearly with distance from the neutral fiber. The top portion of the sample in Figure 8 is in tension while the fibers of the sample below the neutral fiber are in compression. Two lucite wedge surface wave transducers ($67\frac{1}{2}^{\circ}$ angle) were attached to the sample with 1 MHz, X-cut crystals. Once the transducers were put into place they were not removed in order to assure that the path length between the transducers did not change. Surface waves were then generated at 1, 3, 5 and 7 MHz. For each of these four frequencies, velocity changes were noted as the bar was stressed using the measuring system of Figure 1.

The assumption was made that the surface waves would see an average stress depending on the depth of its penetration. The stress on the surface fibers would then be the maximum stress in the sample introduced by loading. If the penetration depth of the wave was to the neutral fiber, then the average stress would be one-half the stress present at the surface since stress increases linearly from the neutral fiber. Note that if the penetration of the wave is the thickness of the sample the average stress would be zero. This results since the wave would theoretically see an equal amount of compression and tension. A simple formula can be used to express the average stress from the surface into the sample and is derived below in Figure 11.

Figure 12 shows a plot of the average stress in percentage of S_{max} that would be present as a function of frequency, i.e., depth of penetration. For the particular sample used a = 0.25 inches. The dots represent the actual data obtained. The data was normalized to the velocity change occurring at 7 MHz assuming a one wavelength penetration. The sample used for the stress gradient study was 1/2" x 2" bar of 2014-T651 alloy. The sample was placed in the loading frame of Figure 8 with the surface wave transducers attached on the 2" side. For thicker samples, it was shown that the average stress near the surface was independent of depth as would be predicted.

E. Surface Conditions

It is therefore apparent that the surface wave can



$S_x = (\text{CONST})\, X$

$S_a = (\text{CONST})\, a = S_{max}$

$$S_{avg.} = \frac{S_{max} + S}{2} = \frac{S_{max}\,(1 + X/a)}{2}$$

Figure 11. Sample Subjected to Constant Bending Moment Defining Fiber Location for Calculating Average Stress Versus Depth.

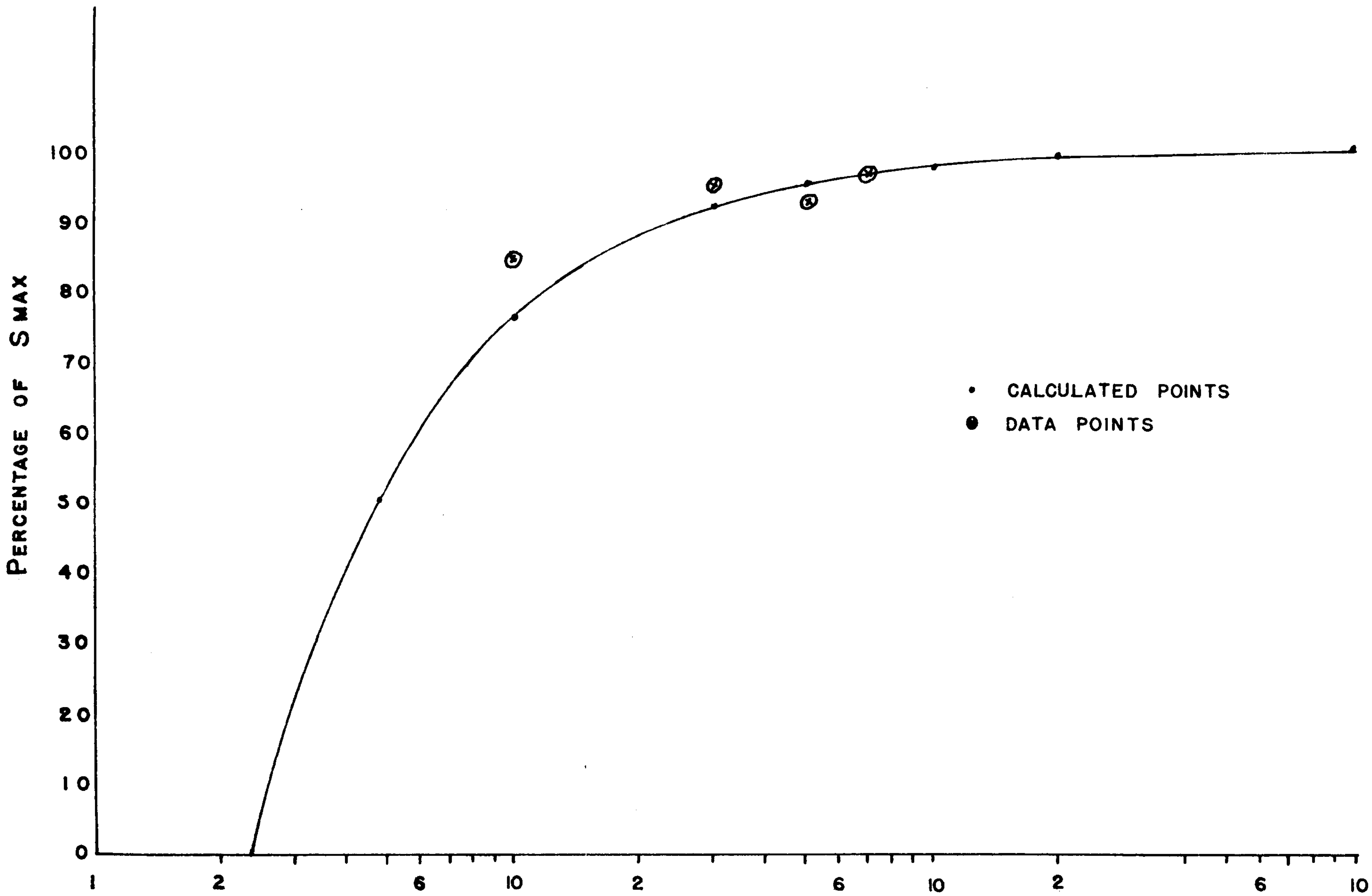


Figure 12. Stress Gradient Measurements Showing Measured Stress and Calculated Stress as a Function of Frequency.

detect and measure a stress gradient. The gradient present in the sample described above is 4×10^4 lbs/in^2 per in. There are, however, factors that must be considered in order to properly interpret the information obtained from surface wave studies of stress analysis before application to field use is possible. One of the foremost factors is the condition of the surface. It is visually possible to tell the surface on several alloys, namely 2024, 6061 and 7075. Since they have different appearance presumably due to naturally occuring oxide coatings. Studies have been made concerning the velocity change of the surface wave with uniaxial load applied as a function of frequency. Results of these studies is shown in Figure 13 for 6061 alloy. The technique employed to obtain the data for the above figure is similar to that used above in the stress-gradient studies with the exception that a uniaxial load was applied. It is seen that the velocity change for a given amount of stress is not as pronounced at 3 MHz as at 7 MHz. There are two possible explanations for the observed behavior. These are: (1) a stress gradient is present in sample as a result of the forming process, and/or (2) the surface is of substantially different composition than the bulk of the material. Evidence that the latter has some merit was demonstrated by milling 1/32 inch from the surface and repeating the experiment. In this case the surface wave velocity change with stress was independent of frequency. The other alloys mentioned above also have a similar behavior.

Another factor which needs attention before accurate field measurements are possible is that the surface wave transducers, generator and receiver, must be rigidly attached to each other in order to keep path length constant. Also in this connection, the transducers must be designed so that the points of generation and reception of the waves remain the same. This implies that if at all possible the transducers will have to perform with little or no couplant. These requirements on the transducer are fairly strong; however, promising development work is now being conducted along this line.

A "knife"-edge transducer has been constructed and is shown in Figure 14. The knife edge has the advantage that

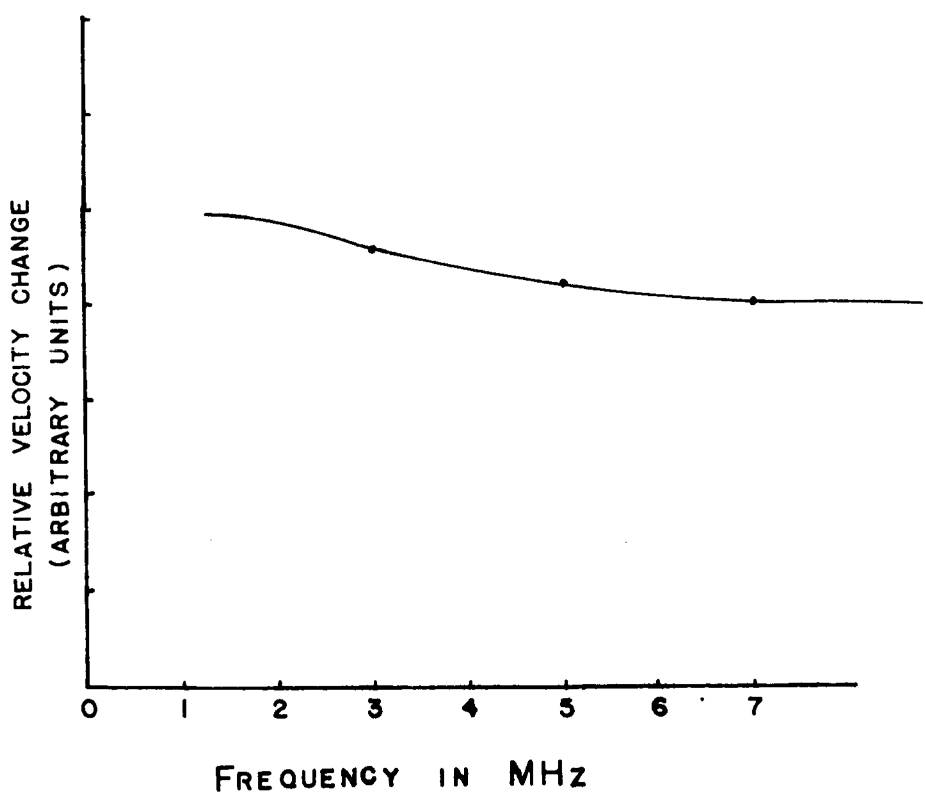


Figure 13. Relative Change of Surface Wave Velocity Versus Frequency for a Constant Stress Applied Uniaxially.

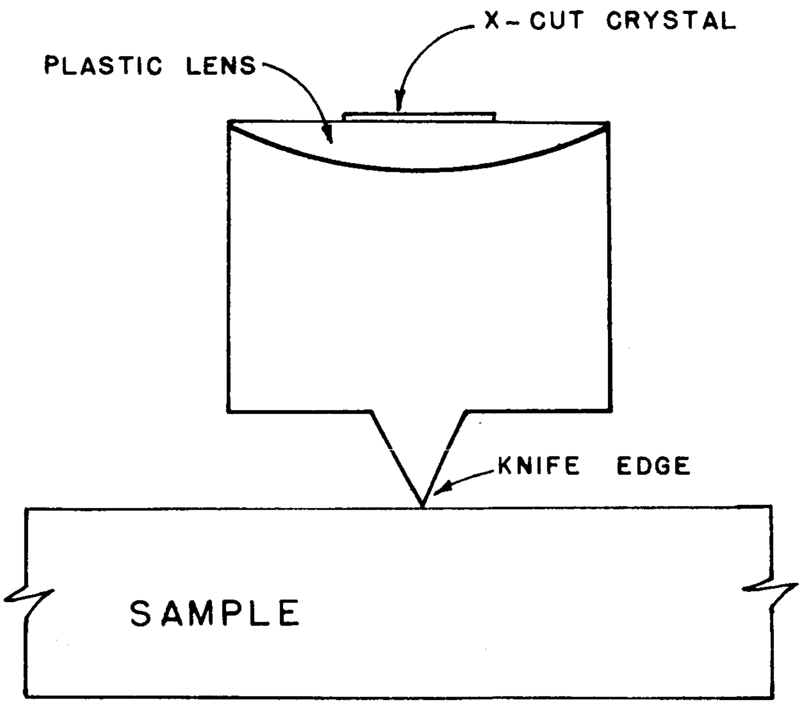


Figure 14. Knife Edge Transducer for Generation and Detection of Ultrasonic Surface Waves.

the place at which the surface wave is generated or received is well defined. With this in mind the path length transversed by the surface wave in the sample can be accurately determined since it is possible to rigidly attach the sender and the receiver. Note that a plastic lens is employed to focus the ultrasonic wave. This is necessary since the knife edge behaves as a line source with the sound rays extending radially from it. The lens diffracts the rays causing them to form a plane wave front. Evaluation of this transducer design is currently underway.

In addition, such a transducer could lead to new techniques by which relative and absolute velocity measurements could be made. These techniques would basically employ a frequency changing method. A signal from the sample under study would be phase-compared to a reference signal. There are two possibilities by which a measurement could be made. These are: (1) the oscillator frequency is changed and the frequency difference for a 360^{0} phase shift is noted, or (2) the amount of change in frequency necessary to initially bring the sample and reference signal back in phase when the sample is stressed. In either case a measurement could be made giving information on the state of surface stress present.

IV. MEASUREMENTS OF FATIGUE AND CORROSION

A. Introduction

Fatigue damage and stress corrosion cause failure to structures even though the static limit of the material has not been exceeded. Both forms of damage are functions of the duration of exposure to either repeated cycling or to corrosive atmospheres when the material is under stress. Although relatively large stresses are involved, they are well within the design limit imposed by static considerations. At the present time design criteria must account for these types of failure which impose more severe restrictions than static design criteria. It would be of extreme value if nondestructive measurement methods were available which would anticipate the failure of a structure by either fatigue or stress corrosion. Although the two methods of failure are quite different in their origin the initiation of failure occurs near the surface of the material in almost all instances. It would therefore seem reasonable that methods which can detect the presence of fatigue damage can also detect the damage due to stress corrosion. Several methods of measurement have been studied using samples which have been subjected to either fatigue or stress corrosion. The objective of these measurements is not to understand the mechanism of failure but to develop non-destructive means which will predict the remaining life of the structure.

B. Sample Preparation

The samples which have been studied have been prepared using commonly accepted methods for producing either fatigue or stress corrosion. The preparation of these samples will be described and the subsequent measurements and results will then be given. For stress corrosion, aluminum samples were subjected to a salt bath where the sample was alternately immersed in a 3 per cent salt solution and then subjected to drying in the atmosphere. The bath was made using de-ionized water with sufficient salt added to produce a 3 per cent solution. The samples were mounted on non-metallic racks in a non-metallic container. The salt solution was pumped into the container from a reservoir which immersed the samples for a period of ten minutes at which time the pump was shut off and the container was emptied. The samples were then exposed to air for a period of 50 minutes and the cycling was repeated. The system was designed in this manner so that loading frames could be introduced in the bath easily to study the effects of stress.

The initial measurements were concerned with the effects of corrosion itself without the introduction of stress other than that possibly due to the machining processes in preparation of samples. A second series of samples were prepared where a uniaxial force was applied causing the sample to be in a state of tension. The entire loading frame and samples were subjected to the salt bath. Two types of loading frames were used, the first of which produced a constant elongation of the sample and the second of which produced a constant force on the sample.

In order to produce fatigue damage two forms of cyclical loading were used. These methods of loading were chosen since some of the apparatus required cylindrical samples while other pieces of apparatus required rectangular samples. The cylindrical samples were subjected to torsion where the rate of cycling was approximately one cycle for every two seconds. The stress level was chosen from information available in the literature which should result in failure by fatigue after approximately 24 hours of excitation. This would correspond to approximately 50,000 cycles for failure.

The rectangular bars were subjected to bending moments where the ends of the bar were supported and the center was deflected in alternate directions. Again, the deflection was chosen to cause failure after approximately 50,000 cycles. A series of samples were subjected to both forms of loading and the time required to produce failure was recorded. The amplitude of excitation was then adjusted to cause failure after approximately 20 hours of excitation. The computed stress corresponded closely to those given in the literature. These particular levels were used so that data could be taken over a reasonable number of cycles but was sufficiently short so that a large number of samples could be prepared within a short period of time. In some cases, it was necessary to remove the sample from the fatigue apparatus in order to make a measurement. At the time of removal, all forms of measurement possible on a given sample were taken and the sample was replaced in the fatigue apparatus. In general, the samples were subjected to approximately one-half of their life before a measurement was taken and continued in one hour increments until failure. After each additional hour of excitation additional measurements were made of the properties of the material.

Samples were prepared from stock either cylindrical in shape or square and the surface was polished with successively fine grit until surface imperfections were removed. In all cases, an initial measurement was made on the sample before subjecting it to either fatigue or stress corrosion. The samples for fatigue were cylindrical, 1/4 inch in diameter, or of 1/2 inch square cross section. The samples for stress corrosion varied from 1/4 inch in diameter to 1/2 inch in diameter. A sample length of $7\frac{1}{4}$ inches was chosen which corresponded to an electrical resonant frequency of 800 megacycles per second and a mechanical resonant frequency of approximately 14 kilocycles per second. Both resonant frequencies were within the range of the apparatus used for measurement so that the same sample could be measured by more than one technique.

C. Basic Measurements Performed for Damage Evaluation

Three basic types of measurement were performed on the different types of samples. Electromagnetic surface resistance and ultrasonic attenuation measurements were selected because of their properties of measuring surface phenomena. The third measurement selected was the mechanical "Q" where the sample is vibrated at its fundamental longitudinal resonance. This additional measurement is sensitive to surface defects but also gives an indication of internal changes in the structure of the metal sample. Furthermore, considerable data was available on samples which gave a good basis of comparison with the effects of damage. The apparatus for measurement for each technique will be described and the results of measurements will be given.

D. Internal Friction Measurements and Results

A valuable quantity to measure concerning the effect of corrosion, fatigue, and stress corrosion is the change of the internal friction of the sample under test. The system shown in Figure 15 shows a block diagram of the apparatus used in order to obtain the measurements. The sample was supported in its geometrical center by two tightly stretched steel wires .01"D, separated by 1/4". The shape of bars used in

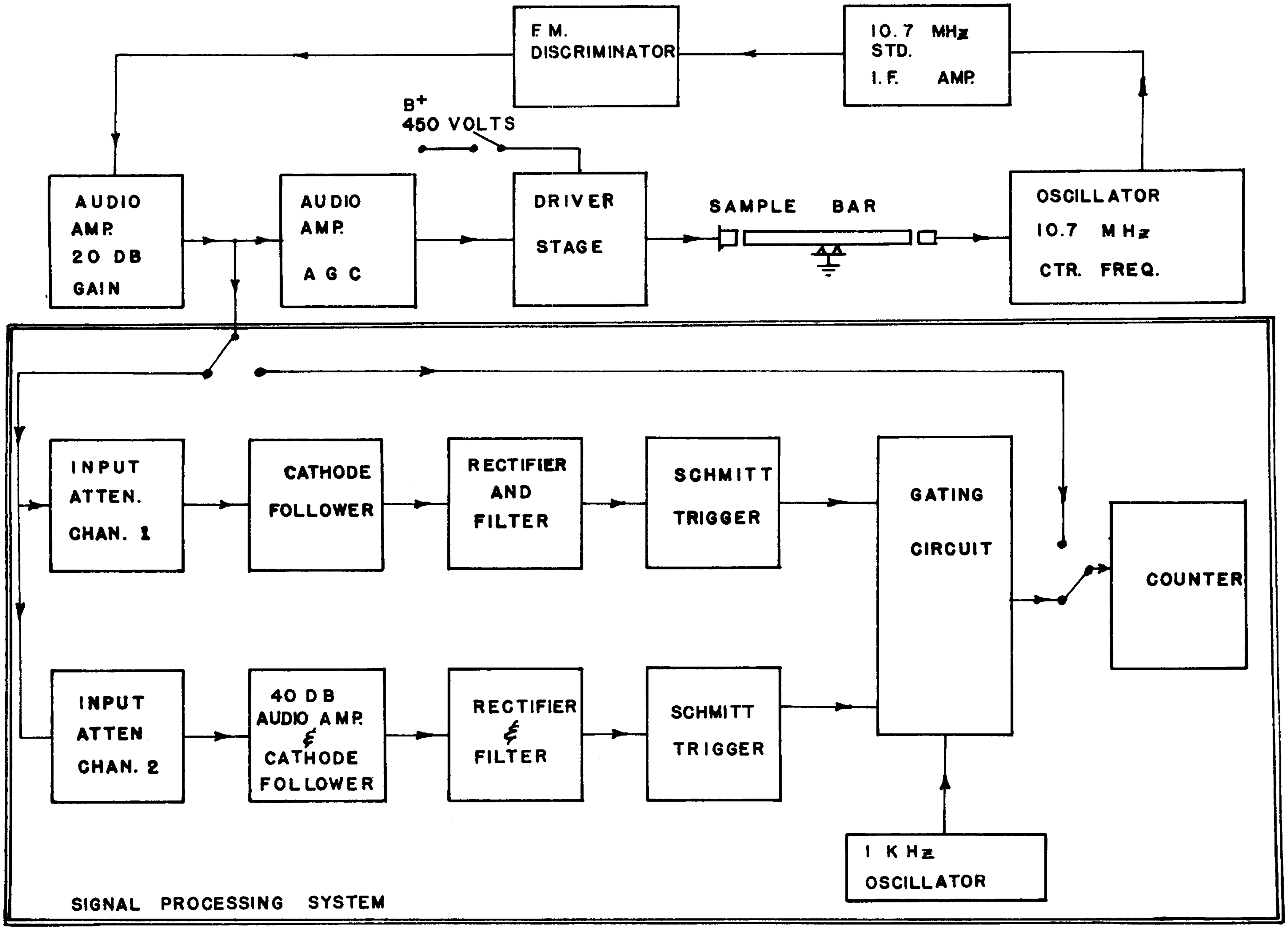


Figure 15. Block Diagram of the System Used to Measure Internal Friction.

the test were cylindrical and had a length of 7.25 inches. The samples were driven electrostatically at one end so that they vibrated in their longitudinal mode. With the given support system, vibration occurred at the fundamental frequency of the bar with a vibrational node at its center. Under these conditions, a bar with a length of 7.25 inches has a fundamental longitudinal vibration frequency of 13,960 KHz. It should be pointed out that the sample is excited in a vacuum in order to eliminate loss by mechanical radiation. The vacuum obtained is on the order of 10^{-3}mm of Hg.

The means by which the bar is driven has the particular advantage that there is no physical contact with the sample. In addition, there is no need to attach any other material to the sample such as the bonding of magnetic material, etc. As mentioned above, the bar is driven electrostatically by the driver stage shown in the Figure. This stage is a 6BG6 operated with a plate voltage of 450 volts. The plate of this tube is connected to a button type of probe with a diameter of 0.25 inch. The sample bar is grounded by means of the center support. (See Figure 16.) When the probe is placed near one end of the bar (approximately 0.005 inch) an AC signal will tend to vibrate the bar as a result of the fluctuating electrostatic force present. The bar will prefer only to vibrate at its fundamental frequency or at an even harmonic.

The vibration of the bar is detected in a fashion similar to the electrostatic driving system. Again, a small button probe is placed approximately 0.01 inch from the sample. The capacitance between the sample and the probe forms part of a resonant circuit in an oscillator operating at a center frequency of 10.7 MHz. The output of the oscillator is then fed into a standard 10.7 MHz IF amplifier followed by an FM discriminator. Therefore, the discriminator output voltage follows the movement or vibration appearing at the end of the sample bar at a frequency corresponding to its fundamental longitudinal mode.

The detector output is fed into an audio amplifier with a gain of 20 db and upper frequency cut off of 20 KHz.

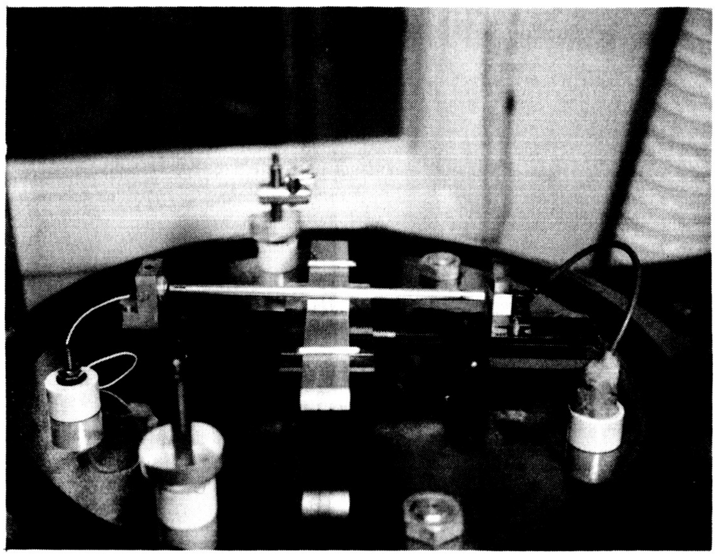


Figure 16. Placement of Sample on Support for the Measurement of Internal Friction.

Figure 15 shows that the signal has two possible paths at the output of the 20 db amplifier. One path leads to the signal processing circuit while the other path leads a second audio amplifier. The second audio amplifier has a nominal gain of 80 db but is equipped with an AGC circuit. This amplifier drives the final driver stage. It is noted at this point from the diagram that the 10.7 MHz oscillator, the FM detector, the audio amplifiers, the driver stage, and the sample form a closed loop system. Also it should be pointed out that the gain in the system, assuming no AGC voltage, is 100 db, and because of the presence of the sample in the system the bandwidth is very small due to the fact that the bar prefers to ring or vibrate at only one frequency. Any type of transient voltage occuring in the amplifiers such as noise will excite the bar. The signal is then received and amplified further and regeneration occurs. As the received signal builds in amplitude the AGC circuit in the second audio amplifier cuts the system gain so that the output of the first 20 db audio amplifier remains linear. A typical voltage level at the output of the discriminator when a bar is ringing is 3.0 volts r.m.s. The AC driving at the driving probe is approximately 70 volts r.m.s.

The signal processing circuits derive their inputs from the first 20 db audio amplifier of the closed loop system described above. This signal is fed into a cathode follower into channel 1 and also into a 40 db audio amplifier into channel 2. The AC signals appearing in each of these channels are rectified and filtered giving DC levels dependent on the amplitude of the input signals. Each channel contains a Schmitt trigger which changes its output voltage abruptly when the input DC level reaches a predetermined value. The outputs of the two Schmitt triggers are then fed into a gating circuit which allows a 1000 Hz signal to be fed into a counter when the states of the two Schmitt triggers are appropriate.

Once the sample is ringing at its fundamental frequency and the output of the discriminator has reached approximately 3.0 volts r.m.s., the plate supply voltage is removed from the driver stage. At this point the closed loop system is opened and the voltage generated by the ringing of the bar begin decaying exponentially. In a similar fashion the DC levels feeding the Schmitt triggers begin an exponential decay following the envelope of the input audio signal from the bar. As the DC level falls the Schmitt trigger of channel 1 changes state allowing the 1000 Hz oscillator signal to be fed into the counter. Further decrease in the DC level appearing in channel 2 causes the second Schmitt trigger to close the gate. The value appearing on the counter is therefore directly proportional to the time the gate was open. Since a 1000 Hz oscillator is used, the time for the opened gate can be read to milliseconds.

The DC trigger points of the Schmitt triggers have been set so that it takes a 10:1 change in voltage level for the subsequent opening and closing of the gating circuit. Therefore, the signal processing system reads directly the time to the nearest millisecond that it takes the bar to decay 20 db. This time is related to the "Q" of the bar by the following formula:

$$Q \doteq 1.365\, f_r t$$

Where f_r is the ringing frequency of the bar and t the time for a 20 db decay. The quantity f_r is found by feeding the input to the signal processing system directly into the counter.

The mechanical "Q" of a vibrator is a measure of the rate of energy dissipation by mechanical means within the sample. These measurements are ordinarily referred to as internal friction measurements, although previous studies in this laboratory showed that the resultant "Q" is dependent upon surface conditions. These findings have been confirmed in the present studies inasmuch as surface defects due to corrosion were easily measured. The initial "Q" of the sample selected can be as much as 500,000 which indicates an extremely small loss of energy per cycle of excitation. The first studies by this method involved the measurement of "Q" for samples subjected to a corrosive bath as described above for varying periods of time. The results of these measurements are shown in Figure 17 which illustrates the decrease in "Q" or increase in loss with time of exposure.

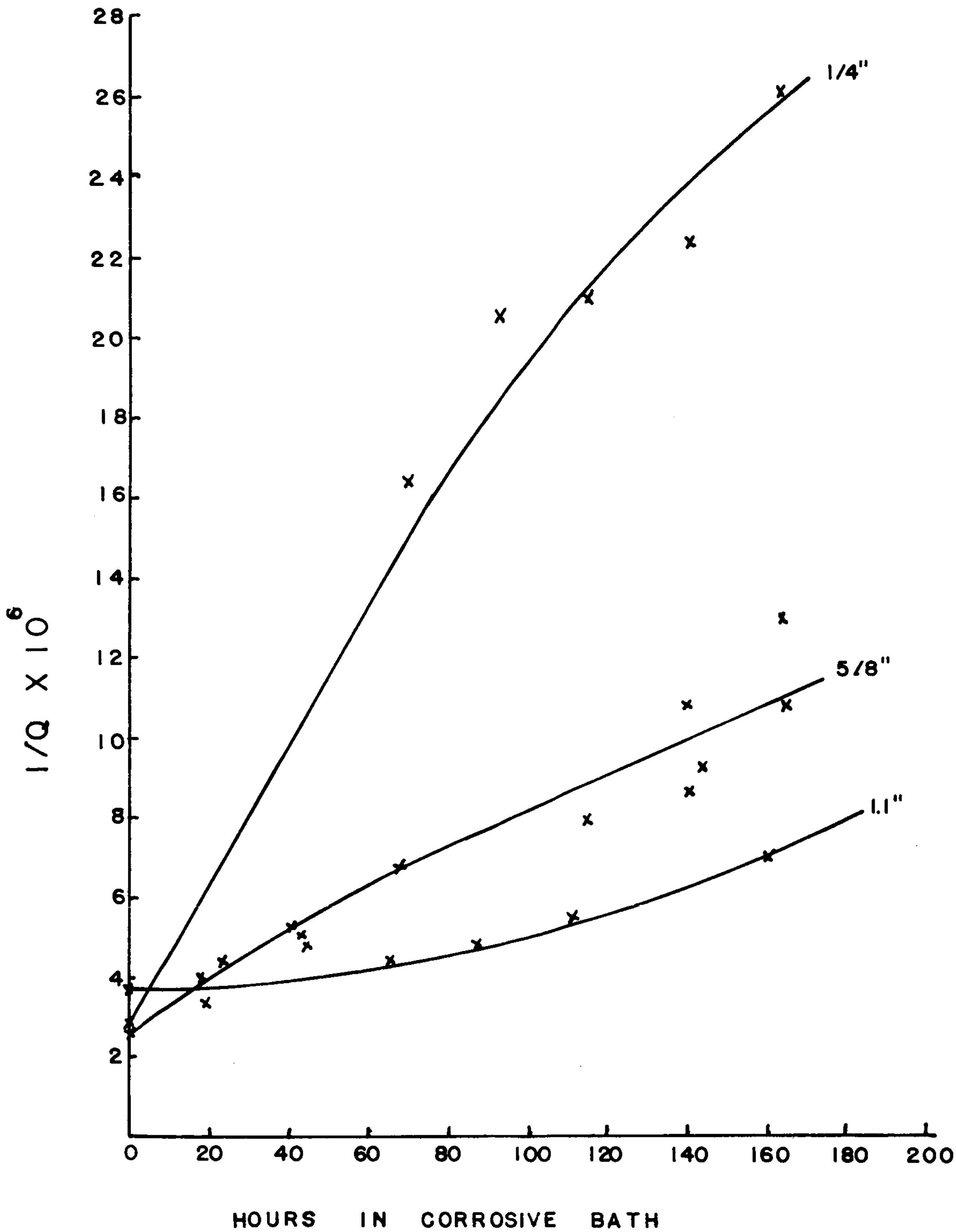


Figure 17. Increase in "1/Q" Versus Time in Corrosive Bath for Various Size Bar.

It is noted that the exposure times are relatively large compared to those exposure times used for studying stress corrosion where the sample is also subjected to tensile forces. In order to establish the fact that the damage due to corrosion was near the surface, successive amounts of the surface were removed by turning the sample in a lathe and the increase in "Q" was measured. The "Q" as a function of the amount of surface material removed is shown in Figure 18. It is noted that the sample returns to its original "Q" after the surface material containing defects is removed. This method allows for a measure of the depth of penetration of corrosion damage. It was also noted visually that all evidence of damage had been removed when the "Q" had returned to its initial value.

The introduction of a tensile stress applied by a loading frame accelerates the damage quite markedly. Unfortunately, the application of sufficient tensile stress causes failure in an extremely short time if the direct effects of corrosion are to be avoided. It was possible to produce as much change in "Q" during a 24 hour period with the introduction of tensile stresses as was found with corrosion alone over a period of two weeks. If the tensile forces are reduced to decrease the rate at which effects take place, the losses can be accounted for by corrosion alone. It therefore is difficult to obtain sufficient data to determine the progress of stress corrosion without the preparation of a large number of samples. Since each sample must be contained within a loading frame during its exposure, the collection of sufficient data to provide a statistically significant result is time consuming. Nevertheless, this method shows a large change in internal friction due to the combined effects of stress and corrosion. At the present time, insufficient data is available to provide quantitative measurement of the effect.

Samples subjected to fatigue were also measured in the apparatus which determines mechanical "Q". An initial measurement was made after sample preparation and subsequent measurements were made as a function of the time which the sample had been subjected to cycling. In all cases the mechanical "Q" remained relatively constant over approximately 75 per cent of sample life and then decreases. The

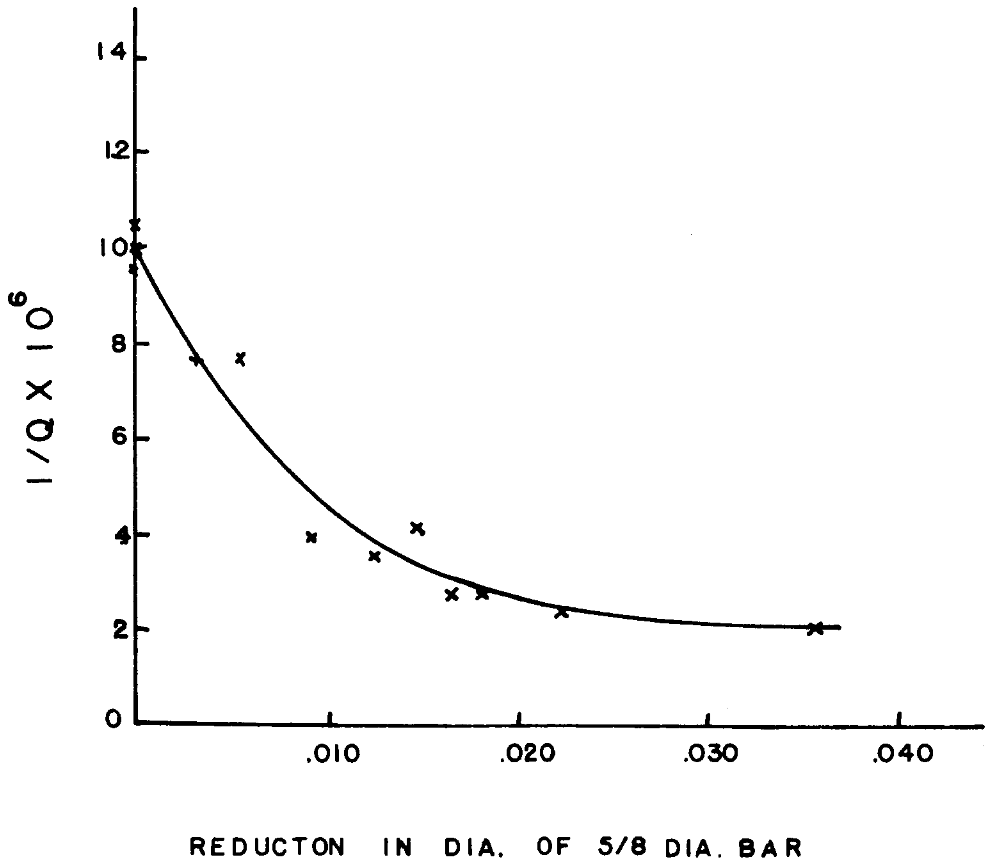


Figure 18. Determination of the Penetration of Corrosion Damage as Determined by Internal Friction Measurements Versus Removal of Damaged Material.

increase in losses indicated that failure was about to occur. In some cases a measurement was made a few minutes before failure of the sample and the "Q" was sufficiently low that it was almost impossible to excite the sample. A summary of the data is presented graphically in Figure 19 illustrating the decrease in "Q" as a function of the number of cycles of alternate stress.

It has been demonstrated that the measurement of mechanical "Q" provides an indication of the defects occuring during either exposure to stress corrosion or fatigue. The method itself is limited to laboratory studies for which the size and shape of the sample can be selected to be compatible with measurement apparatus. It therefore can be a useful technique in laboratory studies but is not readily adaptable to a field measurement.

E. Ultrasonic Attenuation Measurements and Results

Since it has been demonstrated that the effects of stress corrosion and fatigue occur near the surface, it would be anticipated that measurements of ultrasonic attenuation for surface waves would be more sensitive to the progress of damage than the lower frequency measurements reported above. For this reason, measurements using surface waves were made on a number of samples as a function of frequency. The initial measurements were concerned with the repeatibility of attenuation since it is extremely difficult to obtain consistant results. The procedures used involved measuring the amplitude of the surface wave as a function of distance along the surface. The penetration of the surface wave is dependent on wave length and it would be expected that the higher frequencies would be more sensitive to the first stages of damage. Ultrasonic surface waves are easily generated at frequencies up to 10 megacycles by the use of lucite wedges having an angle of incidence of approximately 67° when the material to be inspected is aluminum. Above this frequency the attenuation in lucite becomes so great that it is difficult to generate a sufficiently large surface wave so that it can be used for measurement. Nevertheless, using careful techniques it was possible to generate and

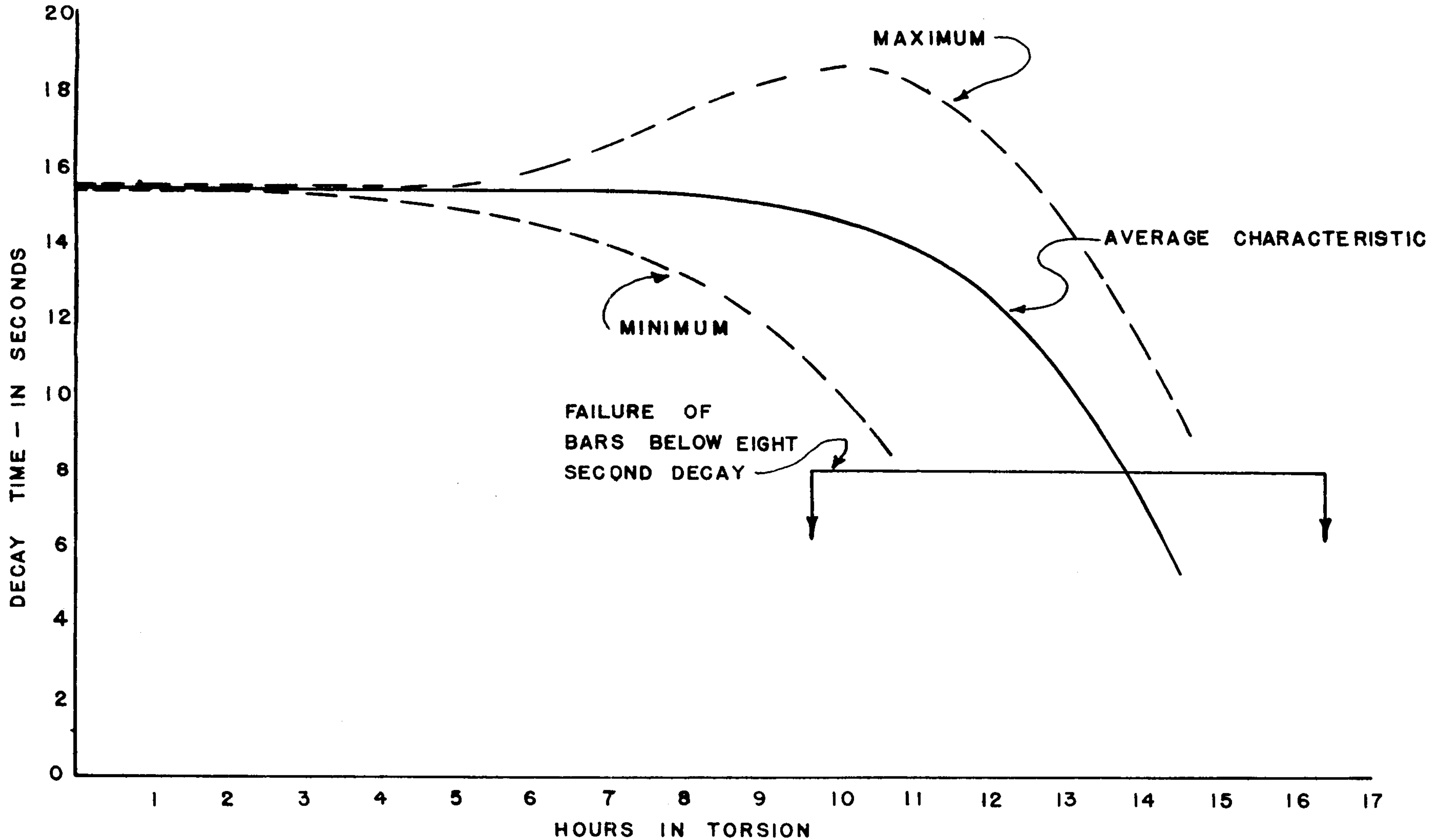


Figure 19. Time Necessary for a 20 db Decay Versus the Time the Samples were Subjected to Torsion. Note Decrease in Decay Time as Sample Nears Fatigue Failure.

detect surface waves up to frequencies of 35 megacycles. This was accomplished by reducing the path length in the lucite to approximately 1/4 inch as illustrated in Figure 20. Even after successfully overcoming problems of generation, difficulty was encountered in repeating measurements. These difficulties are due to the fact that the signal amplitude is a marked function of the coupling to the sample as well as the cleanliness of the sample surface. With sufficient care, it was found that the ultrasonic attenuation was extremely low up to frequencies of 35 megacycles in a newly prepared sample. In order to make successful attenuation measurements it will be necessary to develop a transducer which provides constant coupling to the sample since, in all cases, it will be necessary to move either the generator or receiver to determine attenuation.

Before developing more suitable transducers a series of measurements on various samples was made to determine the possible sensitivity in measuring damage. Measurements were made at frequencies of 1, 3, 5 and 7 megacycles with depths of penetration corresponding to those revealed by internal friction measurements. For samples that are prepared the attenuation over this frequency range is essentially constant. As the samples are subjected to different forms of fatigue, corrosion or stress corrosion, the attenuation at the higher frequencies increases and the frequency at which additional attenuation occurs continues to decrease indicating that the effects are occuring at greater depths from the surface. The measurements which have been made are subject to considerable variability due to the problem of coupling the transducer to the surface. For this reason the measurements shown in the graph of Figure 21 are an average of a large number of measurements and are not indicative of the accuracy that has been obtained. They do show that if accurate measurement methods are developed, the attenuation should show a relationship with the damage caused and further provide a measure of the penetration of the damage beneath the surface of the material. It would be expected that this penetration would correspond to the growth of the damage that is occurring. Recent development of surface wave transducers using a knife edge to contact the surface as described under the stress analysis section of this report should lead to increased accuracy of measurement of surface damage.

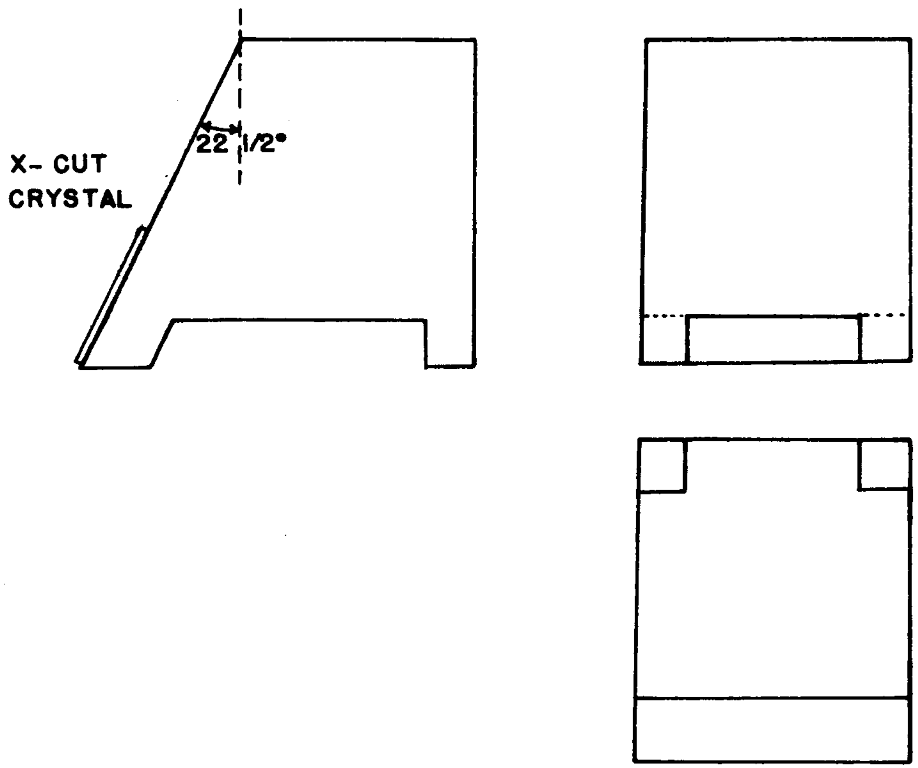


Figure 20. Design of High Frequency Surface Wave Transducers.

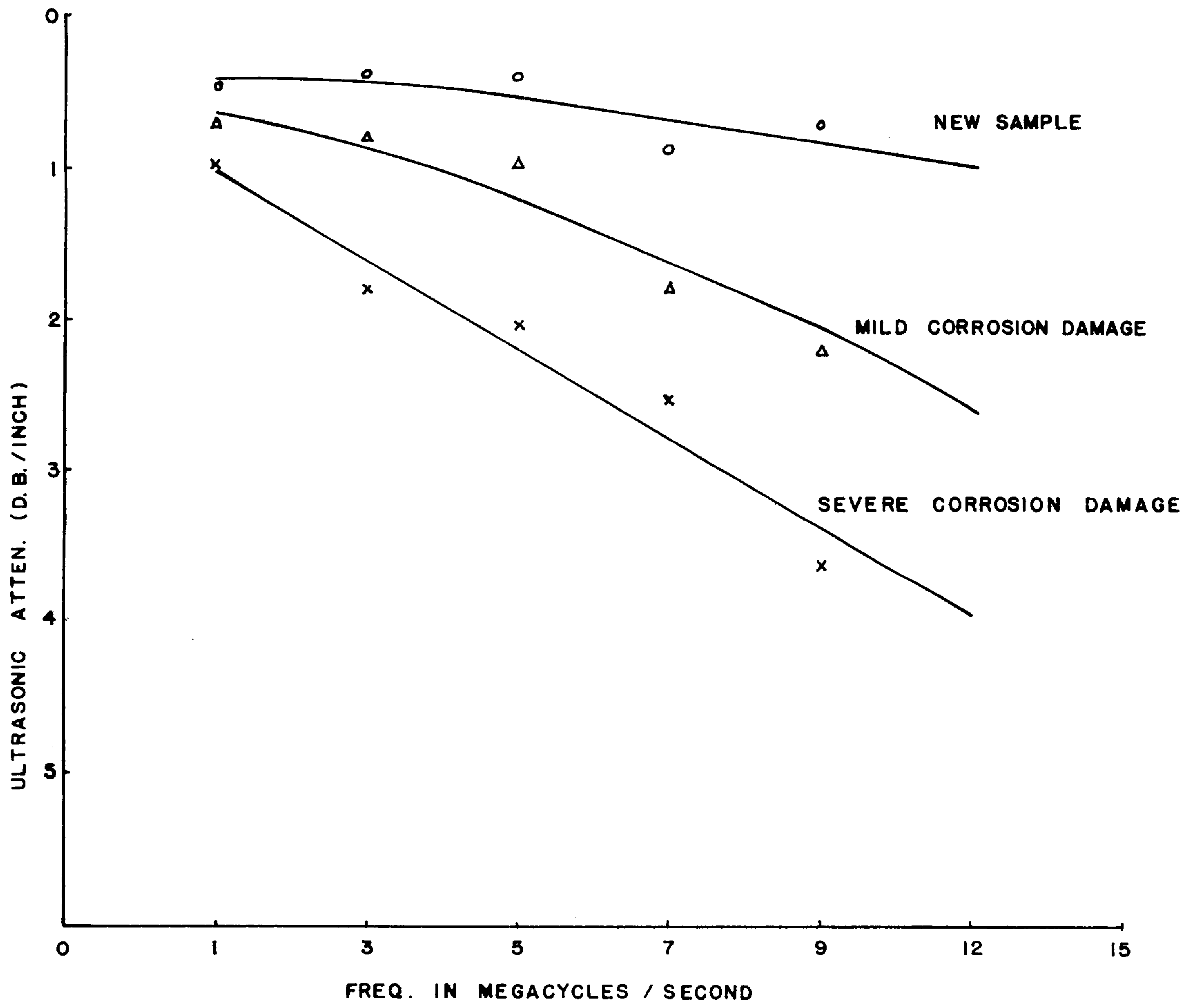


Figure 21. Ultrasonic Attenuation as a Function of Frequency for Aluminum Samples Subjected to Corrosion.

F. Electromagnetic Resistivity Measurements and Results

Measurement methods are available which are comparable to the ultrasonic methods outlined above but where the electrical losses are examined rather than mechanical losses. The internal friction measurements described above not only measure losses near the surface but measure all of those losses in the bulk of a sample. Comparable electrical measurements may be made on a sample by the use of eddy current techniques which have been used extensively in flaw detection. The eddy current technique involves excitation of the sample at low frequencies where the electrical currents are caused to flow throughout the bulk of the material. The energy is coupled to the sample inductively by the use of coils and imperfections are detected by the use of symmetrical coils which are initially balanced for a uniform sample. If sufficient care is used, a large amount of gain may be employed which results in a signal when an imbalance is caused by the introduction of a flaw. Damage caused in a sample by either fatigue or stress corrosion introduces microscopic flaws which usually occur near the surface. If a sufficiently sensitive system is used the sample imperfections may be detected. Such techniques have been used with excitation frequencies up to a few megacycles per second where the eddy currents penetrate most of the thickness of the sample. Under these conditions the methods must detect the presence of sample cracks which are superimposed on the losses already caused by the bulk of the material. In other words, the sensitivity on detecting microcracks near the surface is limited due to the presence of losses distributed throughout the sample due to the inherent resistivity of the sample. Other factors which decrease the sensitivity of the system are imperfections in sample geometry such as slight changes in cross sectional area which are also detected.

It is desirable to increase the sensitivity of the detection of surface cracks without also measuring the bulk properties of the material. For this purpose it is desirable to take advantage of high frequencies where the electromagnetic energy propagates near the surface and the penetration can be controlled. This effect is referred to as the skin effect which results from electromagnetic forces in the conductor. An experimental set-up was designed to use those samples which were also suitable for measurement by the mechanical and the ultrasonic methods which require sample lengths of approximately 7 inches. If the sample is used under conditions of electromagnetic resonance, the length of the sample should correspond to one-half of an electrical wave length. This corresponds to a frequency of measurement of approximately one kilomegacycle for a 7 inch sample. The depth of penetration at this frequency corresponds to 1.1×10^{-4} inches in aluminum. The measurements are accomplished with a system shown in the diagram of Figure 22. The basic oscillator which provides excitation of the sample was a simple, commercially available power oscillator which was modified to incorporate methods for automatically sweeping through a small frequency range as well as a manual method of performing similar small changes in frequency. Provisions were further made to display the sweeping voltage in synchronism with the change in frequency of the oscillator. Small changes in oscillator frequency were produced by incorporating a varactor diode type AEL-CO2400IF in the basic oscillator circuit. The voltage applied to the diode was developed by a simple transistorized saw tooth generator. The output of the oscillator is suitably isolated from the load and is coupled loosely through a probe to the resonant specimen incorporated in a shielding cavity as illustrated in Figure 23. The sample was carefully placed so that a maximum isolation was obtained and the electrical conditions shown in the Figure were accomplished. The losses due to radiation were minimized by placing the ends one fourth wave length from the open ends of the shield tubing.

An output probe was also loosely coupled to the opposite end of the sample. The signal strength was detected with a heterodyne system which produced a 30 megacycle nominal frequency for amplification by an intermediate frequency amplifier. The commercial amplifier was tuned in a manner which provided a broad, constant amplitude versus frequency response over the frequency range of interest. In operation the resonant characteristic could be displayed automatically or the manual frequency control could be varied to provide quantitative measurements of the bandwidth of the resonator

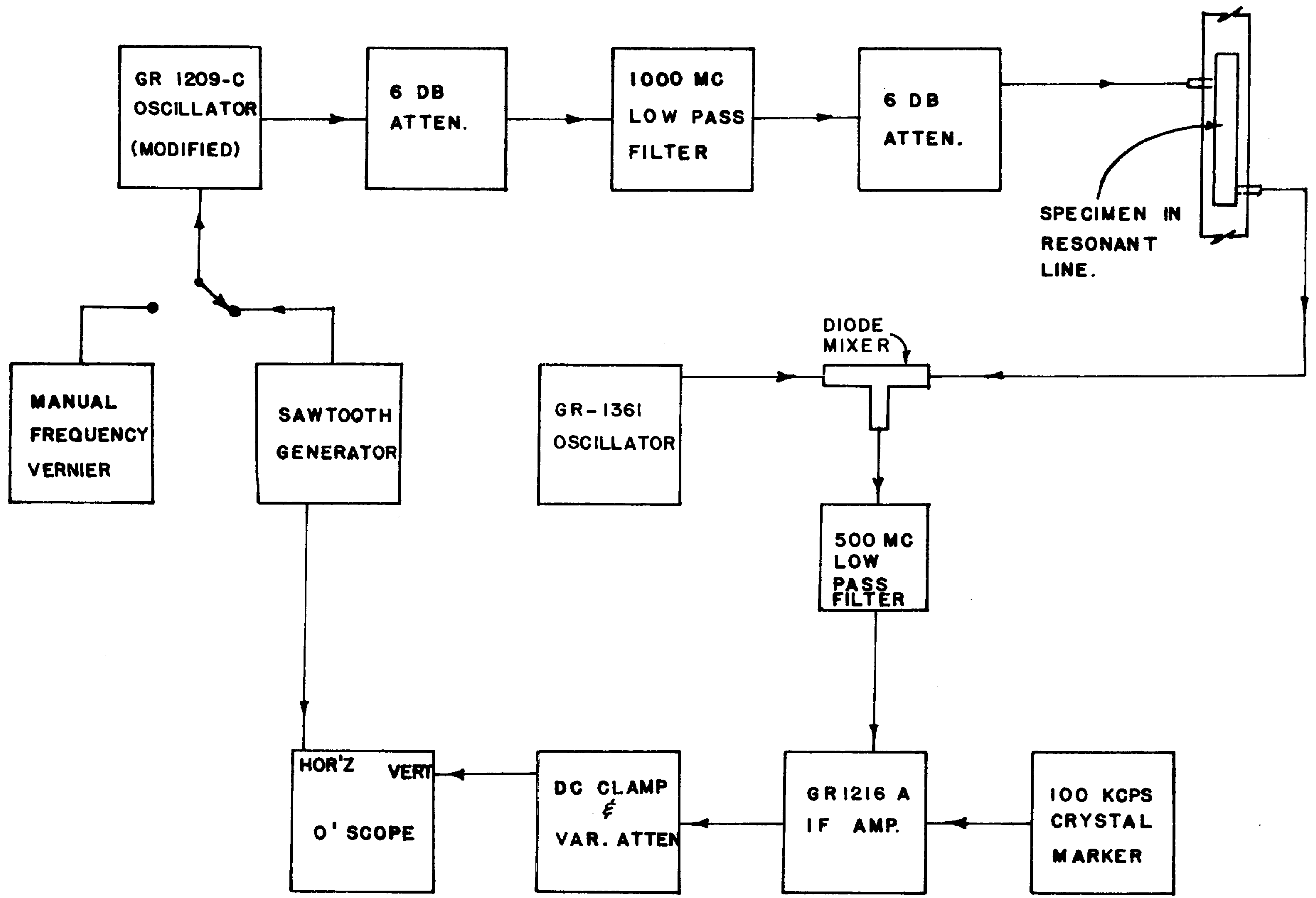


Figure **22** Block Diagram of System for Surface Resistivity Measurements Operating at 800 KMH_z.

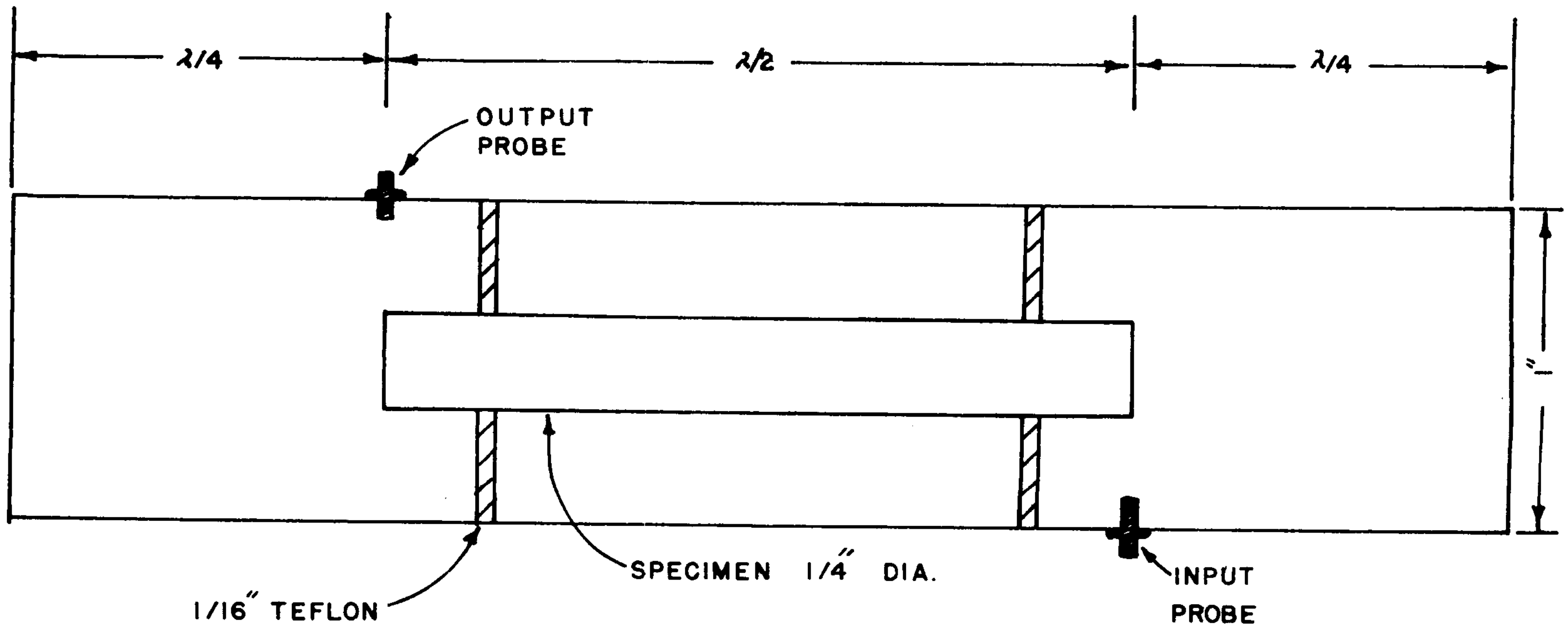


Figure 23. Resonant Cavity Incorporating Specimen for Surface Resistivity Measurements.

comprised of the sample. For calibration purposes a crystal controlled marker generator was used to allow for the determination of the relationship between change in frequency and horizontal deflection of the oscilloscope.

Each sample that was selected for study was first measured to determine the bandwidth of the resonant specimen which is a measure of the losses near the surface of the specimen. The sample was then subjected to either corrosion or fatigue and was again measured to determine any increase in bandwidth which would correspond to an increase in loss.

A number of samples were prepared from a variety of aluminum alloys in the manner previously described. The electrical loss at the surface of these samples was measured periodically as they were exposed to the salt water environment. This loss as a function of time of exposure for a typical sample is presented as Figure 24.

A similarly prepared group of samples was subjected to the previously described torsional fatiguing process and the change of surface electrical loss monitored at hourly intervals throughout the test. The composite results of this experiment is presented as a plot of loss versus cycling time as Figure 25.

In the case of the corrosion test, the corrosion was more or less uniform over the surface of the bar and the electrical measuring technique whereby the surface resistivity was measured for large areas of the sample was quite effective. In the case of the fatigue measurements the fatigue damage tended to be localized whereas the measuring technique still monitored relatively large lengths of the sample. For this reason, the increase of surface resistivity with the onset of mechanical fatigue damage is not nearly so apparent.

As has been stated before, the depth to which the electrical resistance is measured may be controlled by choosing the frequency of measurement. In an effort to localize the measurement axially along the sample a test fixture was made comprising a set of very small, carefully balanced coils which induced very localized eddy currents into the sample. With this arrangement, fatigue damage could readily be observed inasmuch as the measurement was confined to a very

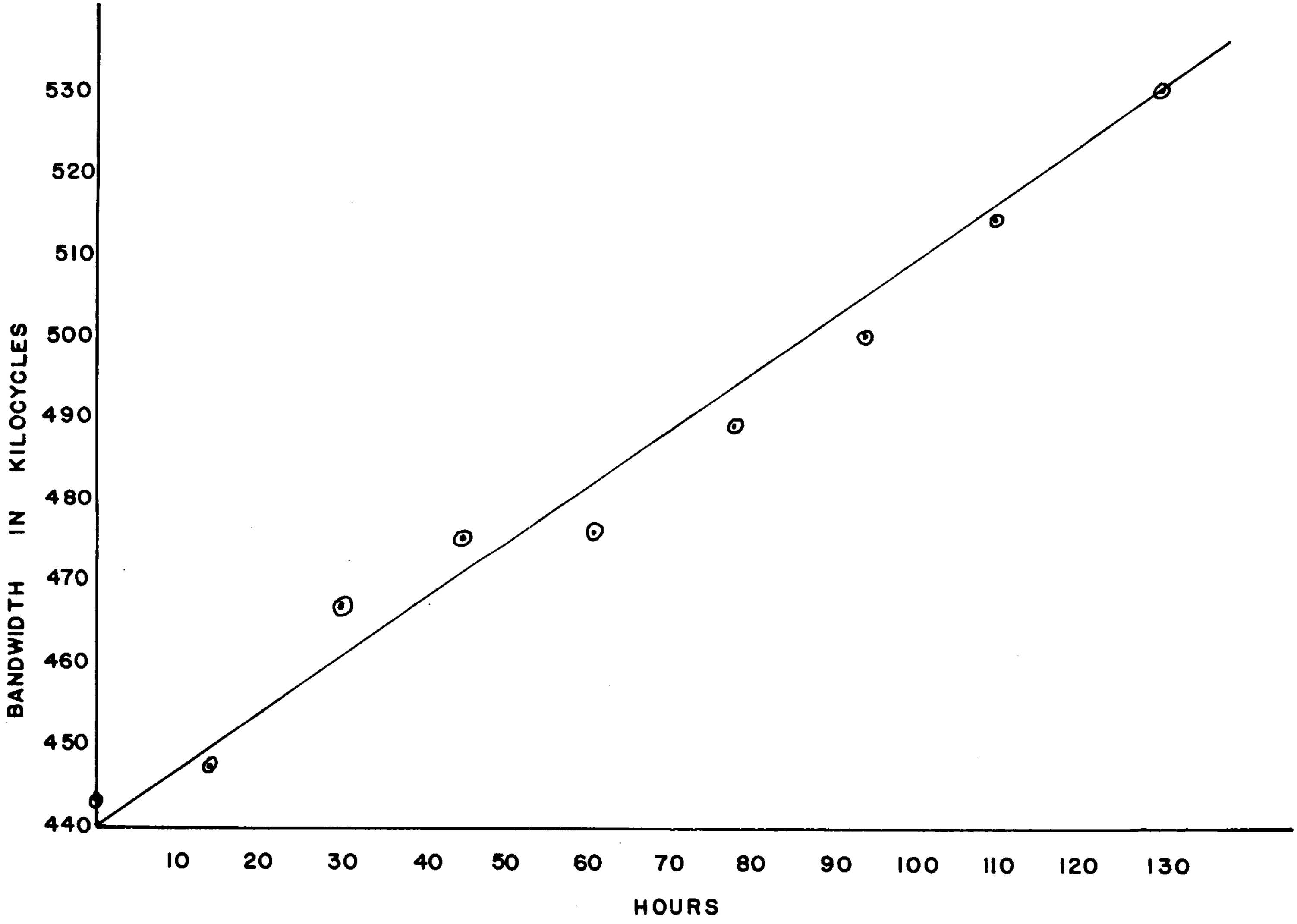


Figure 24. Electrical Bandwidth Increase of a Linear Resonator Incorporating an Aluminum Sample Versus Time Subjected to a Corrosive Bath.

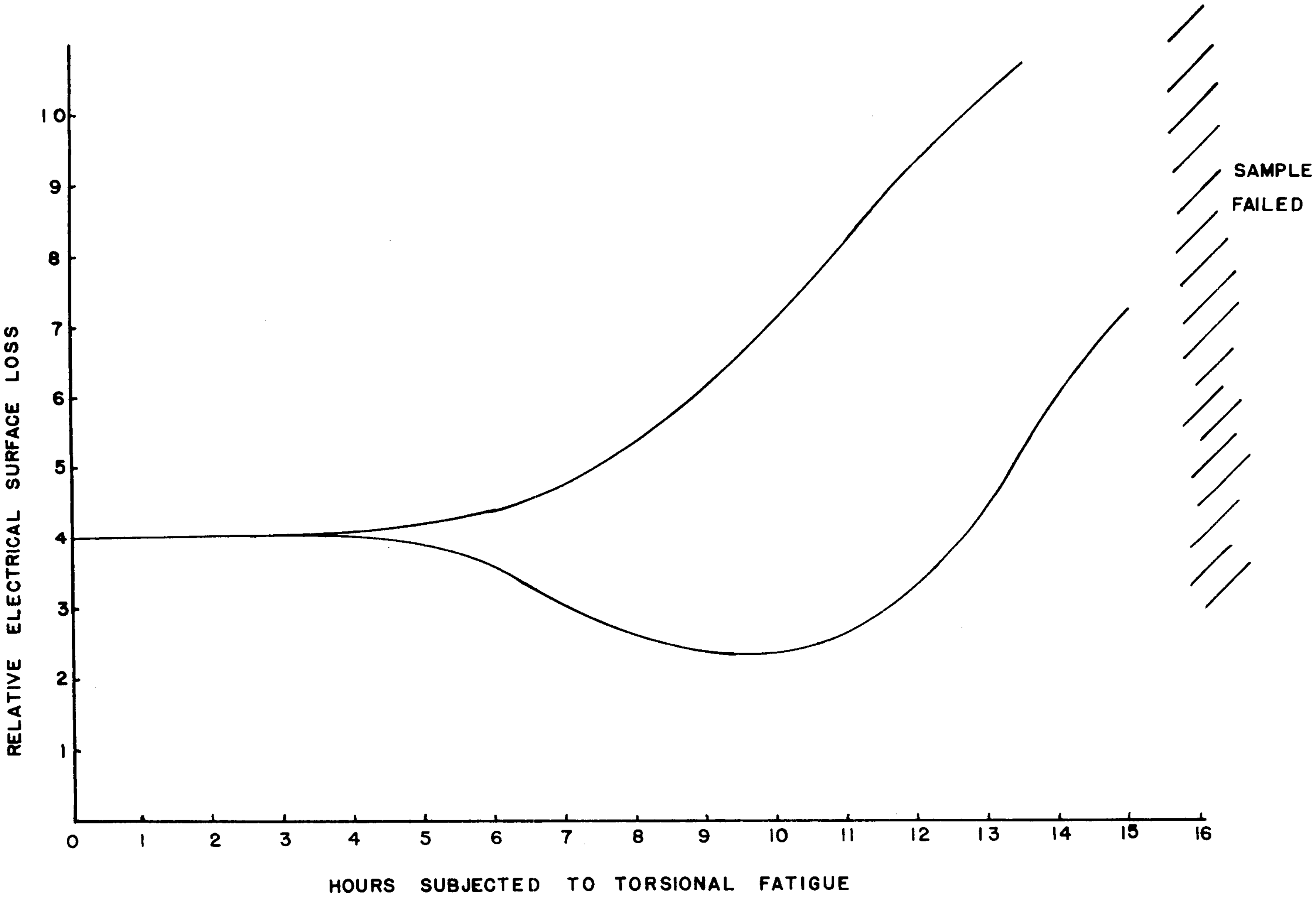


Figure 25. Relative Electrical Surface Loss Versus Hours Subjected to Torsional Fatigue.

small percentage of the total length of the sample. These measurements were made at frequencies generally below one megacycle per second. An extension of this technique to higher frequencies will make possible the localization of measurement not only axially along the sample but also to very small and controlled depths.

V. SUMMARY

Several methods of measuring stress distributions in aluminum samples have been accomplished under laboratory conditions. Uniaxial stresses are accurately measured in specific samples, however, the type of alloy affects the sensitivity of measurement. Stresses near the surface of the material due to bending moments or due to uniaxial forces have been measured and the gradient of stress has also been measured by varying the penetration of ultrasonic surface waves. Requirements for measurement of residual surface stresses have been established and preliminary designs for transducing systems which will allow for these measurements have been completed.

In order to perform accurate field measurements of stress it is necessary to establish repeatable methods of coupling shear wave transducers to actual structures. Several couplants have been studied which show promise of yielding satisfactory results. For surface wave and stress gradient measurements it is necessary to provide transducers where the path length for the surface wave is accurately defined. The knife edge transducer produces a good surface wave with accurate control of path length. The frequency of the ultrasonic wave must be controlled by using a continuous wave oscillator which is passed through a gated amplifier since pulsing of the ultrasonic signal is required.

Measurements of change in ultrasonic attenuation of surface waves and of electrical resistivity have been shown to be influenced by the state of damage near the surface of samples which have been subjected to either stress corrosion or fatigue. Requirements for accurate measurements which would allow for inspection criteria have been established. Considerable data must be taken to establish a correlation between the measured phenomena and the state of damage before successful application of these methods is possible.